ACOUSTIC PROPERTIES AND SHOALING BEHAVIOR OF ATLANTIC REDFISH (SEBASTES SPP.)

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By

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A thesis submitted to the School of Graduate Studies

In partial fulfillment of the requirements for

The degree of Doctor of Philosophy

Department of Biology, Faculty of Science

Memorial University of Newfoundland

August 2001

St. John's Newfoundland

Thesis abstract

Acoustic properties, shoaling behavior and diel vertical migration of Atlantic redfish (*Sebastes* spp.) were studied with the objective of enhancing the basis for acoustic assessment techniques. The acoustic target strength (TS) of redfish was measured using both *ex situ* and *in situ* methods. To conduct *ex situ* experiments, a technique was developed to maintain captive individuals alive for study in an experimental set-up using a split-beam echosounder. Techniques of *in situ* TS estimation were also studied in detail and approaches to minimize biases are proposed. Systematic bias in TS occurred above a certain density threshold. The measurement scale used to estimate density influenced the threshold level. Deep-tow dual beam and hull-mounted split beam systems were used to measure the TS of redfish at sea (*in situ*) under various environmental and biological conditions. After controlling for effects of thresholding, fish density, reverberation volume, range, and avoidance behavior, *in situ* and *ex situ* data did not differ and were pooled to obtain a TS-length model of TS = 20Log[length(cm)]-68.7.

Redfish exhibited strong patterns of diel vertical migration and many diverse types of shoaling behavior at several spatial scales, both of which can affect acoustic and trawl survey results. During vertical migration, TS did not change significantly and it appears that redfish have an endogenous cycle for the control of swimbladder gas. Catch data indicated increased mean fish length with depth, while length standard deviation was highest in shallow areas. Pelagic schools of various size and density were most evident in spring and summer. The extent of vertical migration appeared to be limited by differential hydrostatic pressure and related to light condition and feeding.

Acoustic-trawl experiments indicated that bottom trawl catches consistently underestimated redfish density. Acoustic assessments were biased downward during the day, because an increased proportion of fish occupied the near-bottom acoustic dead zone (DZ) and there was increased heterogeneity in distribution. This work suggests that the most accurate and least variable estimate of redfish abundance can be achieved using acoustics during the night, when fish are dispersed in the water column and most available to acoustic measurement.

Acknowledgements

I would first like to thank my supervisor, Dr. George A. Rose, for his perceptive mentoring and for always leading by example. His acuity in identifying and addressing problems was crucial to the success of this work. His enthusiasm and devotion to science were constant sources of inspiration. I also appreciated support and suggestions from my supervisory committee members: Drs. Brad deYoung and Joe Brown. I would like to acknowledge the Hydroacoustic Division of the Northwest Atlantic Fisheries Centre in St. John's, Newfoundland for assistance and guidance with acoustic instruments. Christopher Lang was very helpful in the elaboration of ideas and in the assimilation and analyses of acoustic data. Christopher Stevens provided many insightful comments and suggestions. I would like to thank several people for their valuable assistance at sea: most importantly Wade Hiscock, Dennis Ivany, Michael Norris and the crews of the CCGS Teleost and CCGS Shamook. I would also like to thank Dr. Paul Snelgrove and peers from the Fisheries Conservation Chair for support. Fellow graduate students provided many stimulating conversations, moral support and assistance. Finally but not least, I would like to thank my wife, Catherine, for her love. She always kept me cheerful and mended my spirit when in need. Funding for this project was provided by the Department of Fisheries and Ocean's Redfish Multidisciplinary Research Program and the Natural Sciences and Engineering Research Council of Canada Industrial Chair in Fisheries Conservation at Memorial University of Newfoundland.

Le plus grand des mercis à mes parents et ami(e)s, pour leur amour et leur support.

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Symbol	*Description*	*Units*
	-Chapter 1-	
TS	Target strength	dB
	-Chapter 3-	
V	Volume	ml
p	Pressure	atm (atmospheres)
a	Slope for the TS-length relationship	-
b	Intercept for the TS-length relationship	dB
	-Chapter 4-	
N_v	Number of fish relative to 1 sampling volume	numbers
c	Sound speed	$m \cdot s^{-1}$
τ	Pulse duration (pulse width)	s
ψ	Equivalent beam angle	steradians
R	Range	m
n_{EI}	Fish density obtained from echo-integration	numbers $\cdot$ m^{-3}
S_v	Volume scattering coefficient	dB
T_v	Number of targets relative to 1 sampling volume	numbers
n_{EC}	Fish density obtained from echo-counting	numbers $\cdot$ m^{-3}
Ω	Cut-off angle of the beam	degrees

N_Ω	Number of targets inside the cut-off angle	numbers
V_Ω	Volume of the beam at the cut-off angle (cone)	m^3
a_R	Radius of a cone at range R	m

-Chapter 5-

TS_i	Target strength at depth i	dB
c_i	Sound speed at depth i	$m \cdot s^{-1}$
TVG	Time Varied Gain	dB
α	Absorption coefficient	$dB \cdot m^{-1}$
c_0	Default sound speed	$m \cdot s^{-1}$
G_0	Transducer gain at default sound speed c_0	dB
α_0	Absorption coefficient at default sound speed c_0	$dB \cdot m^{-1}$
t	Time of signal arrival from transducer to target and back	s
t_i	Observed time of signal arrival at transducer depth i	s
R_i	Observed range of target at transducer depth i	m
c_{avg}	Average sound speed for a depth interval	$m \cdot s^{-1}$
R_{ref}	Actual range of target to transducer	m
$Bias_i$	TS bias at depth i	dB
K	Fish condition factor	$g \cdot cm^{-3}$
w	Fish weight	g
l	Fish length	cm
TS_c	Target strength corrected for transducer hysteresis	dB

TS_o	Observed target strength	dB
d_T	Transducer depth	m
$\hat{\sigma}_{bs}$	Average backscattering cross-section of fish	m^2

-Chapter 6-

TS_A	Target strength at depth A	dB
TS_B	Target strength at depth B	dB
P_A	Pressure at depth A	atm
P_B	Pressure at depth B	atm

-Chapter 7-

$\bar{P}$	Pressure ratio	unitless
P_{max}	Pressure at the bottom	atm
P_{min}	Pressure at the upper range of migration	atm
$\dot{S}_v$	Volume spherical scattering coefficient (logarithmic)	dB
s_v	Volume spherical scattering coefficient	m^{-1} ($m^2 \cdot m^{-3}$)
σ_{sp}	Spherical scattering cross-section	m^2
σ_{bs}	Backscattering cross-section	m^2
π	Pi, the ratio of the circumference of a circle to its diameter (= 3.1415926535897793)	-
D_v	Volumetric fish density	numbers $\cdot m^{-3}$
W	Width of a fish shoal	m
$W_{echogram}$	Measured width of a fish shoal on a echogram	m
θ_3	Half power angle of the beam at the -3 dB points	radians

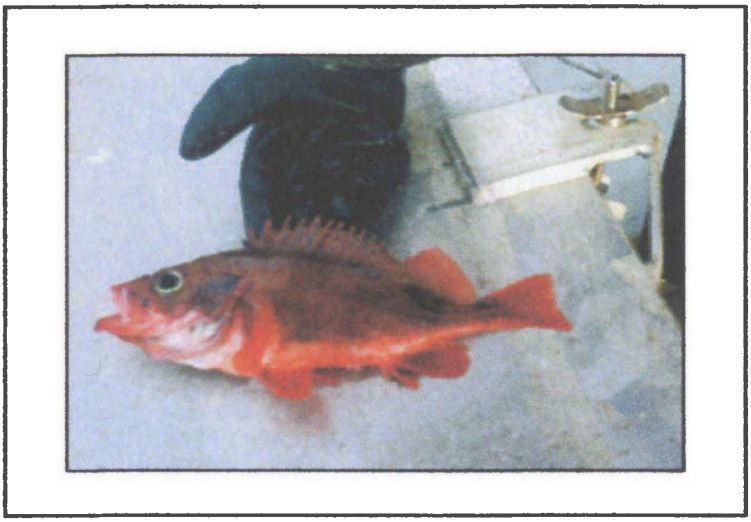
r_{max}	Maximum range of a shoal	m
r_{min}	Minimum range of a shoal	m
H	Height of a shoal	m
$H_{echogram}$	Measured height of a shoal on a echogram	m
$\overline{D}_v$	Mean fish density inside a shoal	numbers $\cdot$ m^{-3}
A	Area of a shoal measured on the echogram	m^2
Alt	Altitude of a shoal above bottom	m
d_{shoal}	Mean depth of a shoal	m
$S_v^{\ p}$	Volume scattering coefficient in the pelagic zone (spherical)	m^{-1} ($m^2 \cdot m^{-3}$)
x	Radius of the for and aft axis of a fish body	m
y	Radius of the lateral axis of a fish body	m
z	Radius of the vertical axis of a fish body	m
V_f	Volume occupied by a single fish	m^3
BL	Body length	body length

-Chapter 8-

s_a	Area scattering coeficient	$m^2 \cdot m^{-2}$
D_a	Area fish density	numbers $\cdot$ m^{-2}
h	Height of the dead zone	m
d	Depth	m
WS	Wing spread of the trawl	m
N	Number of fish	numbers

v	Vessel speed	$m \cdot s^{-1}$
T	Tow duration	s
X	Distance of the net behind the vessel	m
L_w	Length of wire deployed during a net tow	m
CV	Coefficient of variation	-
BL_{10}	Proportion of fish in the 10 m layer above bottom	- (percentage)

Chapter 1. Introduction and Overview



1.1 General note on redfish

The *Sebastes* genus (family Scorpaenidae, subfamily Sebastinae) includes more than 100 catalogued species, most of which are found in the Pacific Ocean (rockfishes). In the Atlantic, four species are currently recognized: *Sebastes viviparus* (small redfish), *S. marinus* (golden redfish), *S. mentella* (deep-water redfish or ocean perch), and *S. fasciatus* (Acadian redfish). In the Northwest Atlantic, *S. viviparus* is absent and *S. marinus* is relatively uncommon, except around the Flemish Cap (Scott and Scott, 1988). *S. mentella* and *S. fasciatus* are collectively named beaked or sharp-beaked redfish, because of a small anterior protuberance on their lower jaw. These species are difficult to distinguish using external features and it is only recently that they have been accepted as distinct. Techniques used to differentiate them include anal fin rays count, malate dehydrogenase mobility patterns, extrinsic gasbladder muscles passage, and the use of parasitic copepods as natural biological tags (Rubec et al. 1991, Moran et al. 1996). Anal fin rays count has limited success and other techniques are impractical and labor intensive. Recent evidence of broadscale introgressive hybridization between the two species further complicates the issue of discrimination (Roque et al. 2001). In Canada, beaked and golden redfish have been managed together in the fishery.

All three species are ovoviviparus (Wourms 1981). The eggs are fertilized and brooded within the ovaries and females extrude relatively undeveloped larvae. *Sebastes* are typically long-lived and slow growing species. The longevity of *S. mentella* was estimated to be at least 65 years (Campana et al., 1990). Recruitment variability is high

and poorly understood. In Atlantic Canadian waters, significant year classes have been observed only infrequently in the past few decades at 5 to 12 year intervals. Assessment and management strategies employed for population reference levels have been the same as those applied to other groundfish (DFO, 2000). However, strategies based on target exploitation rates have proved to be unworkable in recent years, due to inaccuracy in biomass and fishing mortality estimates. The history of redfish exploitation in Atlantic Canada will be outlined in the next section, with emphasis on the Gulf of St. Lawrence and Laurentian channel areas. Management of redfish stocks has been complicated and inconsistent, and points to the need for better assessment methods and accurate information on the ecology of these species.

1.2 The redfish fishery in the Northwest Atlantic

In addition to the constant pressure of the Canadian and American fisheries, many European countries have exploited the Northwest Atlantic since the early century (Travin and Pechenick, 1963). By the 1950s more than twelve countries sent boats regularly to catch groundfish in the Gulf of St. Lawrence and off the coast of Newfoundland and Labrador. The exploitation level was particularly high between 1950 and 1960. In 1949 the International Commission of the Northwest Atlantic Fishery (ICNAF) was formed and started to carry out scientific and commercial investigations. The Soviet fleet was particularly interested in the redfish resource and most of their efforts seemed to aim in that direction from 1955 to 1960. Soviet landings increased 2.7-fold between 1938 and 1955 and catch exceeded 100 000 tons · year^{-1} of redfish by 1960 (Yanulov, 1963).

When management of the stock became imminent, the question of dividing the Northwest Atlantic redfish into different stocks was at the base of a long and yet unresolved problem (Martin, 1953; Wise and Jensen, 1960; Mead and Sinderman, 1961; Kohler, 1968; Sandeman 1973). In the early 1970s this problem was complicated by indications that fish thought to be *S. mentella* were actually of two different species (Barsukov and Zhakharov, 1972), now identified as *S. mentella* and *S. fasciatus*. More systematic assessment of the redfish populations began in the same period (ICNAF, 1973) and management units for redfish were determined (Parsons and Parsons, 1975; Parsons et al., 1976). A total of eight redfish units were assigned in the Northwest Atlantic: NAFO div. SA 2 + 3K, 3LN, 3M, 3O, 3P, 4RST, 4VWX and SA 5 (Fig. 1). Evidence to support the appropriateness of those areas as representative of distinct redfish stocks was often absent, inconsistent or contradictory (Atkinson and Power, 1991). However, those units were the basis of redfish management up until the 1990s. By that time, a renewed interest was directed at this resource because of the decline in other fisheries, namely the collapse of the Atlantic cod (CAFSAC 1989; Parsons and Lear, 1993; Walters and Maquire, 1996).

A renewed interest in redfish led to detailed surveys being carried out in waters of the Gulf of St. Lawrence and the Laurentian Channel area. Acoustic data indicated, among other things, a continuous distribution of redfish in the Laurentian channel (CAFSAC, 1990). This information led researchers to believe that the redfish in 3Pn and

4Vn (off the south coast of Newfoundland) and redfish in 4RST (Gulf of St. Lawrence) were not really distinct stocks or that interactions were more pronounced than had been assumed in the management plan. This information strengthened doubts about stock structure previously expressed for those areas (Kenchington, 1982; Zwanenburg, 1985). It was hypothesized that the redfish population of the Gulf migrated to waters off the south coast of Newfoundland during winter. Atkinson and Power (1991) consequently reformulated 3 management units for the Laurentian channel. These new units comprised a seasonal component following indications of the migration. The 3 new units were defined as:

Unit 1 = 4RST (Jan. to Dec.) + 3Pn (Jan. to May) + 4Vn (Jan. to May)

Unit 2 = 3Pn (Jun. to Dec.) +4Vn (Jun. to Dec.) + 3Ps4VsWfgi (Jan. to Dec.)

unit 3 = 4Wdehkl (Jan. to Dec.) + 4X (Jan. to Dec.)

Since reorganization of the data was necessary, it was not possible for Atkinson and Power to reevaluate fishing quotas. The TAC (total allowable catch) was therefore kept at 102 000 tons (1990s TAC) and partitioned between the 3 new units using records of the average proportion of redfish caught in the respective areas between 1981 and 1990. Nonetheless, the new management units were not adopted in the 1992 groundfish management plan (Morin and Bernier, 1993). Instead, a transition measure allowed fishermen in 4RST units to catch 15% of their quota in the 3Pn units. Furthermore,

vessels that normally had quotas in the 3P and 4VWX units did not have restriction for the 3Pn and 3Vn units. In 1993 the new management units were finally adopted.

In Unit 1 (Gulf of St. Lawrence) the TAC was then set at 60 000 tons. The history of the fishery in that area revealed two significantly high peaks, with more than 130 000 tons of redfish caught in 1973 and 72 000 tons caught in 1992. Stratified-random groundfish surveys (DFO, 1996) indicated a decreasing biomass index since 1990 and this trend coincided with the decline of the commercial fishery catch-per-unit-effort. Following these indications, the TAC was lowered to 30 000 tons in 1994 and the fishery was closed in 1995. Furthermore, seasonal closure of Unit 2 was imposed during the winter to protect the Unit 1 redfish while migrating out of the Gulf. Fishing in the Unit 1 has remained closed or at very low levels since. In Unit 2 (Laurentian channel), landings reached their highest values in the early seventies (between 40 000 and 60 000 tons · $year^{-1}$) due to increased catch by foreign fleets. Since declaration of the 200-mile limit in 1977, catches have been taken mainly by Canadian vessels. Foreign pressure has been concentrated in the 3O NAFO division since 1977. Catches in unit 2 were at their lowest in 1984 (8100 tons) and increased to 27 000 tons by 1993. Subsequent yearly landings have leveled off to approximately 10 000 (TAC level). The major concern at present is that the *mentella* stock has not provided a strong year class in many years. The reasons for this lack of recruitment are unknown

Because of the collapse of other groundfish fisheries, the apparent decline in redfish and the growing concerns of the industry for this resource, a joint Industry-DFO workshop was held in June 1995 to identify priority issues related to the management of the stocks in the Northwest Atlantic. In 1996, a National Redfish Multidisciplinary Research Program was proposed. The steering committee was composed of 5 scientists and 3 representatives of the fishing industry. More than 30 primary investigators from Newfoundland, the Maritimes, and Quebec were involved in the different research components of this program. The four major research fields were:

1. Species identification and stock structure
2. Improved stock assessment and management approaches
3. Distribution in relation to environmental conditions
4. Recruitment studies

Incorporated in this larger framework, my study focuses on the utilization of acoustics as survey tool to assist better stock assessment management. Acoustics were also used to assess the shoaling behavior and small-scale distribution patterns of Atlantic redfish, and how these are influenced by environmental conditions. The ultimate goal was to aid in the design of more suitable surveys and management plans for these species, and improve knowledge of their ecology. More reliable estimates of the abundance, the temporal and spatial structures as well as the ecology (including food-web interactions) of fish populations are essential to the development of fisheries science and management.

The historical inconsistency between scientific surveys and commercial catch, in addition to the failure of management strategies, has left managers and scientists in a position where they are quite likely to be criticized and blamed for any fishery collapse. Although the decision-making processes have often ignored the more conservative recommendations made by the scientists, the focus on science is not entirely ill founded. Inaccuracy of traditional catch-per-unit-effort and estimations of population reference levels points to the need for reasonable alternatives. In my opinion, acoustics is the most promising tool to improve our knowledge of many aquatic resources, such as *Sebastes*. Without necessarily solving all the problems inherent to the estimation of adequate fishing quotas, acoustics can provide more realistic and timely estimations of population size and distribution patterns at various spatio-temporal scales.

1.3 Fisheries acoustics

Basic theories of acoustic wave propagation were proposed by Rayleigh (1877). Kimura (1929) achieved the first successful detection of fish using underwater acoustic waves. In this experiment, sound was transmitted from a projector installed on the side of a pond containing fish. After reflection from the opposite side of the pond, the transmitted signal was collected in a separate receiver. Kimura noted significant changes in the returned signal when fish were inside the sound beam. Sund (1935) published the first echogram of fish ensonified by a downward looking sound source. With the rise of World War II, underwater acoustics made significant progress as the military developed systems to recognize submarines and discriminate fish schools (Mathisen, 1992). It was,

however, only in the 1970s that acoustics became a fisheries assessment tool, owing to the echo-integration technique proposed by Dragesund and Olsen (1965).

Acoustic instruments are relatively expensive and adequate assessment requires extensive surveys, combining trawling gear and echosounder. Moreover, the relative complexity of the instruments and the required comprehension of acoustics for their utilization have, in the past, frequently discouraged more conventionally-minded fishery biologists (Rose, 1992). The lack of trained field engineers and adequate training programs in acoustics have also limited its application. Furthermore, acoustic technicians have often been laboratory-oriented and hesitant to go to sea (Venema, 1992).

In the Northwest Atlantic, acoustics have yet to be utilized quantitatively in redfish stock assessment. Acoustic-trawl surveys for redfish have been conducted by Russia, Iceland and Germany (Orlowsky, 1990; Drevetnyak, 1993; Magnusson et al. 1994; Hammer and Kosswig, 1996; Vaskov et al. 1998; Grzebielec, 1998). Despite these efforts, relatively little information on the acoustic properties of redfish exists. Accurate estimates of the target strength and shoaling behavior of fish species are essential for the interpretation of acoustic survey results (MacLennan and Simmonds, 1992). Scaling of acoustic information is based on linearity between the intensity of returned acoustic signal and the number (and size) of organisms ensonified (Foote 1983). The amount of signal returning from a single fish is not only a function of frequency and system parameters (Horne and Clay 1998), but is species dependent and varies according to

many physiological and behavioral aspects (MacLennan and Forbes 1984, Olsen 1990, Ona 1990).

1.4 Thesis overview

In this thesis, I examine the acoustic properties and shoaling behavior of beaked redfish (*Sebastes* spp.) in the Northwest Atlantic. Two approaches were used to measure the target strength (TS) of redfish, in order to produce a comprehensive TS-length model for these species. In Chapter III, TS was measured on encaged live individuals. This *ex situ* method enabled the measurement of fish of known size under controlled conditions. A technique to capture fish and keep them alive was developed, and TS was measured with the use of a custom-made experimental compound built at sea. *Ex situ* experiments are most useful for the interpretation of observations made in the wild. Some inherent problems related to the measurement of TS *in situ* are explored in chapter IV. I address biases in TS caused by multiple target scattering. TS was observed to increase when the number of fish per sampled volume was above a critical value. Furthermore, I found that the distance over which density estimates were obtained significantly affected the density value for unbiased estimation of TS. Several recommendations are made and diagnostic tools are proposed. In Chapter V, I present a comprehensive study of the *in situ* TS of redfish. The effect of range-induced threshold, depth of the fish, and avoidance behavior are studied by means of a deep-tow dual beam system. Furthermore, I compare results obtained with the dual beam to those obtained with a hull mounted split beam echosounder.

Behavior of fish plays an important role in the interpretation of TS and acoustic surveys. For example, diel vertical migration can significantly affect the availability of individuals to trawl and acoustic surveys. Furthermore, diel movements can change the properties of the swimbladder (*via* Boyle's gas law), hence the TS of fish. In Chapter VI, I propose that redfish undergo an endogenous cycle in the secretion and resorption of swimbladder gas. Observations of TS *in situ* and an experiment on an encaged redfish support this hypothesis. In Chapter VII, the shoaling behavior and diel vertical migration of redfish are explored in more detail. I examine the effect of depth on vertical migration behavior, shoaling structure and size segregation. I attempt to link variations in shoaling structure to ecological (i.e. foraging, predation) and environmental conditions (pressure, temperature). I also describe the acoustic characteristics and internal structures of redfish pelagic schools. Finally, in Chapter VIII, the effect of vertical and horizontal distribution heterogeneity on trawl and acoustic estimates of redfish density are examined. Diel changes in the local variance of fish distribution are assessed and recommendations for improved assessment strategies are made.

The area chosen for this study was located on the edge of the Green and Grand Banks of Newfoundland in NAFO division 3Ps, where redfish could be observed year-round in large monotypic shoals. Most redfish collected were juveniles, suggesting that the area might serve as a nursery ground (D. Power, Department of Fisheries and Oceans, *personal communication*). Oceanographic conditions at the selected sites were ideal for acoustic experiments. In brief, these were 1) the presence of large redfish shoals with

little or no contamination by other fish species, 2) a smooth sea floor (absence of large rocks and boulders) with prominent scattering properties, 3) a relatively unbroken bathymetry (continental slope), and 4) a relatively constant profile of salinity and temperature.

Anal fin ray counts were performed throughout the study (subsample of approximately 100 fish per mission) in an attempt to identify redfish species. This method indicated that most individual measured were of the *mentella* type. However, microsatellite DNA data from this area revealed a high incidence of hybridization between *Sebastes mentella* and *Sebastes fasciatus* (Roque *et al.* 2001). Throughout the study, only 5 specimens of *Sebastes marinus* were identified (based on morphometrics and coloration). Specimens collected in Trinity Bay for the *ex situ* experiments were also identified as *Sebastes mentella*. The results of the anal fin ray counts were often inconclusive, but no other identification techniques were available. However, *Sebastes fasciatus* tend to have a more southern distribution and are infrequent in this region (Roque *et al.* 2000).

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1.6 Figures

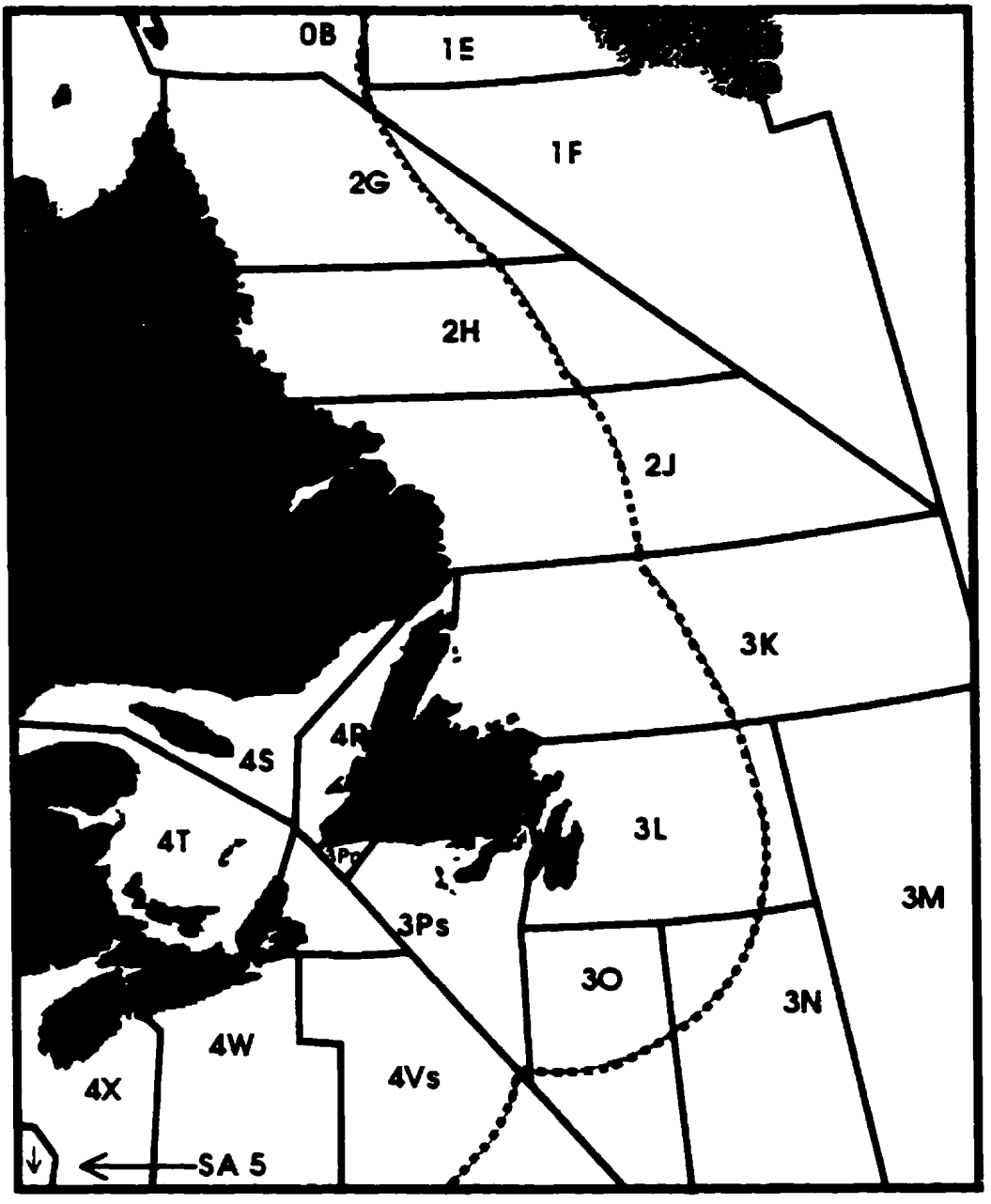

Figure 1.1. Northwest Atlantic Fisheries Management Divisions. The dotted line represents the 200-mile limit. Only a small portion of SA 5 is shown, which extend further down South. Map modified and redrawn by permission of the Memorial University of Newfoundland Cartographic Laboratory, Department of Geography.

Chapter 2. Co-authorship Statements

I am the main and first author on all the research papers included in this thesis. I designed and planned the esperiments and participated in the collection of data. I performed the analyses and wrote the manuscripts. Dr. George A. Rose is a second author on all papers and contributed to the elaboration of ideas and experimental plans and made many editorial comments on earlier drafts of the manuscripts.

C. Lang (Senior Hydroacoustic Metrologist, Northwest Atlantic Fisheries Centre, St. John's, NF) contributed to the elaboration of acoustic calibration experiments, handling of acoustic instruments at sea and analysis of dual-beam data.

Publication and submission status:

Chapter III (Gauthier and Rose) is published in the *ICES Journal of Marine Science* **58**: 562-568.

Chapter IV (Gauthier and Rose) is published in the *Canadian Journal of Fisheries and Aquatic Sciences* **58**: 2149-2155.

Chapter V (Gauthier and Rose) was submitted to the *ICES Journal of Marine Science*.

Chapter VI (Gauthier and Rose) is in press in *Fisheries Research*.

Chapter VII (Gauthier and Rose) was submitted to the *Journal of Fish Biology* (accepted)

Chapter VIII (Gauthier and Rose) will be submitted to the *ICES Journal of Marine Science*.

Chapter 3. Target Strength of encaged Atlantic redfish (*Sebastes spp.*)

3.1 Abstract

Redfish (*Sebastes spp.*) were caught at sea with feather hooks, kept alive in sea cages for > 12 hours at 30 m depth, then transferred to cages at 10 m depth for another 12 h. Most fish survived this procedure in excellent condition. A total of 16 fish of length 24.5 to 30 cm were placed one at a time in an acoustically inert monofilament cage where target strength (TS) was measured for 2 hours using a 38 kHz split-beam echosounder. An underwater video camera enabled continuous monitoring of fish and cage. The best fit length based regression obtained from these data was TS = 19 log [length (cm)] -66.6, in the standard format: TS = 20 log [length (cm)] - 68.1 (R^2 = 0.18). TS varied by less than 4 dB over a range of tilt angles from -50° to 70° off dorsal aspect.

Key words: Redfish, *Sebastes spp.*, target strength.

3.2 Résumé

Des sébastes (*Sebastes* spp.) ont été capturés à la ligne, gardés vivants à l'intérieur de cages marines pendant plus de 12 heures à 30 mètres de profondeur, puis transférés dans des cages à 10 m de profondeur pour un autre 12 h. La plupart des poissons ont survécu cette procédure et étaient en excellente condition. Un total de 16 sébastes de longueur 24.5 à 30 cm ont été placés un à la fois dans une fine cage de monofilament ou l'indice de réflexion acoustique (IR) a été mesuré pour 2 heures utilisant un système à faisceaux partagés de 38 kHz. Une caméra sous-marine a permis une évaluation continue du sébaste et de la cage. La relation entre la longueur et l'IR obtenu était IR = 19 log [longueur (cm)] -66.6, et IR = 20 log [longueur (cm)] -68.1 pour le modèle standard. L'IR a varié par moins de 4 dB pour une série d'inclinaisons de -50° à 70° par rapport à l'aspect dorsal.

3.3 Introduction

Redfish (*Sebastes spp.*) are abundant and long-lived shoaling fishes that inhabit the shelf regions of the north Atlantic. Redfish are similar in morphology and in behavior to the many species of Pacific *Sebastes*. Redfish and other *Sebastes* have large swimbladders, exhibit semi-pelagic shoaling behavior and undertake regular vertical migrations. These features suggest that acoustic survey methods may be appropriate for these species (Eliassen et al., 1994; Magnuson et al., 1994; Vaskov et al., 1998). However, little work has been done on the acoustic properties of redfish or other *Sebastes*, in particular target strength (TS).

There are several methods to determine TS (Foote, 1991). These include modeling, *in-situ* and *ex-situ* experimentation. *Ex-situ* experiments allow fish of known size to be measured under known environmental and behavioral conditions (eg. Edwards and Armstrong, 1984; Goddard and Welsby, 1986; Mukai and Iida, 1995; 1996). However, the manipulation of live fish can affect their behavior and physiology, both of which can impact TS (Foote, 1980a; Ona, 1990). Indeed, for species such as *Sebastes* that are sensitive to pressure change, and deep water species in general, capturing live individuals and keeping them in good condition is difficult.

Sebastes are physoclystic (closed swimbladder) and are very sensitive to sudden changes in pressure. In the ocean, pressure increases uniformly with depth (for each 10 m increase in depth, the hydrostatic pressure increases by 1 atm). According to Boyle's

law, for an ideal gas of a given mass at constant temperature, the volume "V" is inversely proportional to pressure "p" (equation 1).

(1) $$V \propto p^{-1}$$

Hence, swimbladder volume is expected to increase more rapidly at shallower depths. For example, a doubling in swimbladder volume would be predicted if fish moved from 30 to 10 m depth (50% decrease in pressure). At 390 m depth, a fish would have to move 200 m upward in order to produce the same effect. Physoclysts must resorb or secrete gas to maintain neutral buyancy (Steen, 1970). Gas secretion and resorption rates are insufficient to maintain a constant swimbladder volume at the speeds of vertical migration that has been observed in many marine fish (Bone et al., 1995). It is believed that those fish experience neutral buoyancy only at the upper range of their migration (Blaxter and Tytler, 1978). Experiments on cod (*Gadus morhua*) and saithe (*Pollachius virens*) indicated that reducing the pressure to one third caused rupture of the swimbladder (Tytler and Blaxter, 1973). For safe decompression of these species a sequence of rapid reductions in pressure equal to 50% of the current adaptation level was suggested (Tytler and Blaxter, 1973). After each step, 5 h was allowed for resorption of excess gas.

Little is known about the swimbladder response of redfish during vertical migration. However, redfish are seldom encountered close to the surface in the region of

greatest potential swimbladder volume dynamics. This would suggest that the swimbladder of redfish is not as elastic as for species that frequent shallower waters. Redfish that are brought to the surface are typically bloated with air, with the expanded swimbladder obstructing their gills. Stomachs are frequently inverted and protruded through the mouth, indicating that the swimbladder is ruptured and the gas expelled into the body cavity. Individuals that appear in good condition often float, presumably because the volume and buoyancy of the swimbladder make a return to deeper water problematic. Even when caught in shallow waters (40 m) and brought to the surface slowly (0.5 m per min), redfish typically exhibit this bloated condition (Dennis Ivany, commercial fishermen, Petley, Newfoundland, personal communication).

In this paper, I report a technique that allowed me to capture redfish and keep them alive at sea in marine holding cages. I present results of acoustic TS experiments made on these captive redfish in an ocean compound under controlled conditions.

3.4 Material and Methods

This study was conducted from August 19-26, 1999, in Trinity Bay, Newfoundland. Beaked redfish (*Sebastes mentella* and/or *S. fasciatus*) were captured off Petley, Smith Sound, at depths between 50 and 70 m using feather hooks on hand lines (Fig. 3.1). Fish were retrieved as gently as possible and once at the surface were visually inspected for external damage (i.e. perforation of stomach or bulging eyes). Redfish judged to be in good condition were placed in cages (0.36 m x 0.54 m x 1.22 m, 4 cm

mesh size) and immediately lowered to 30 m depth. No more than 8 redfish were placed in each cage. After a minimum of 12 hours, the cages and fish were brought back to the surface for transfer to the nearby experimental site (Fig. 3.1). At the surface, cages were immediately submerged in large plastic tanks holding sea water at ambient temperature and transported using an FRV (Fast Rescue Vessel) to the experimental site. At the experimental site, cages were lowered to a depth of 10 m. The total time that fish stayed at the surface was approximately 20 minutes. After the cages were in place at the experimental site, autonomous divers inspected the cage and the redfish. Following this inspection, a minimum of 12 hrs further acclimation was allowed before any other manipulation was performed. Using this procedure, more than 50% of the fish initially captured survived and appeared to be in excellent condition. The survivors were very active and swam normally. Fish judged to be in less than excellent condition were released. Several escaped while being handled by the divers and displayed vigorous swimming activity.

The experimental set-up consisted of a series of 10 floating platforms (each with dimensions 1 m x 2 m) arranged in a 2 x 4 rectangle, anchored to the bottom at one side and attached to the Canadian Coast Guard Ship Shamook at the other (Fig. 3.2). The CCGS Shamook was secured next to a deep wharf (total depth 11 m). A 38 kHz split-beam transducer was mounted on another platform moored in the middle of the floating set-up. Suspended on the transducer axis from that platform were a tungsten-carbide calibration sphere at a range of 6 m (TS = -42.3 dB at a sound speed of 1490 ms^{-1}) and

the fish cage apparatus at 8 m (fig. 3.3). The apparatus consisted of two large aluminum frames (2.5 m x 2.5 m) that stretched out a cage made of nylon monofilament (0.5 mm diameter) with a mesh size of 2.5 cm (amplitude of the empty cage was –74 dB). The cage dimensions were 0.32 x 0.50 x 0.78 m (0.125 m^3, ignoring distortion due to stretching). The frames were 2 m above and below the cage. The upper frame was outside the acoustic beam (half-power 3.5°) and was not detected in the acoustic signal at a threshold of –70 dB. An underwater video camera was installed next to the set-up to allow constant monitoring of the fish and apparatus during daylight hours. The video camera was also set outside of the acoustic beam and did not produce interfering echoes. Individual fish were transferred from the holding pens to the acoustic cage by divers. The divers then cleared the transducer face of air bubbles and returned to the surface. Each fish was acoustically assessed for at least 2 hours, after which it was measured, weighed and dissected to examine the condition of the internal organs, especially the swimbladder. In total, 21 fish were subjected to this protocol.

Acoustic measurements were made using a SIMRAD EK500 and ES38B split-beam transducer (7.1°) employing a transmit pulse duration of 0.8 ms at 1 ping s^{-1}. The maximum gain compensation was set to 3 dB and the maximum phase deviation between the split-beam quadrants to 2 phase steps, where 1 phase step is equal to 2.8125 electrical degrees difference in the carrier frequency. The acoustic data were initially edited to remove signal attributable to other fish (mainly cunner *Tautogolabrus adspersus* and Atlantic cod *Gadus morhua* that were attracted to the apparatus), using information from

the simultaneous video monitoring and observation of the echotrace from the redfish. For 4 individuals, temporary entanglement of the fish in the mesh of the cage enabled measurements at known tilt angles. Angles were estimated using video images and divers observations with an accuracy of ± 5°. Tilt angles were positive when the head of the fish was higher than its tail and inversely for negative angles. Only events during which fish were positioned with the dorsal and ventral surfaces in line with the acoustic axis (no roll) were included in the analysis.

Means, medians and percentiles of TS were arithmetically determined from the backscattering cross section of the fish prior to logarithmic transformation (Foote, 1987). TS-length regression models were generated for fish at the normal swimming aspect (near dorsal) as TS (dB) = a log [length (cm)] + b and TS (dB) = 20 log [length (cm)] + b. TS of fish measured at various non-zero tilt angles (under temporary entanglement) were not included in the model but were used to estimate directivity.

3.5 Results

Of the 21 fish measured, 16 were judged to have remained in excellent condition throughout the experimental period and had swimbladders and all other organs that appeared to be in place and intact upon post-mortem examination. Swimbladders were observed to be pear-shaped with the bigger part at the anterior end (Fig. 3.4). All individuals measured were females with non-reproductive ovaries. Fish length ranged from 24.5 to 30 cm and weights ranged from 239 to 431 g.

The shape, spread and kurtosis of the TS histograms varied considerably among individuals (Fig. 3.5). Sample size (*i.e.* number of acoustic measures) varied according to time spent in the cage and interference by free-swimming fish. On several occasions, large Atlantic cod (estimated length > 60 cm) took a resting position on top of the acoustic cage, sometimes for more than an hour. Such events interupted the usable data from the encaged redfish.

Mean TS of the 16 redfish measured at normal swimming aspect (near dorsal) ranged from –37.5 dB to –41.4 dB (Fig. 3.6). The best fit regression of TS on length was TS (dB) = 19 log [length (cm)] – 66.6 (95% CI -67.2 to -66.0; R^2 = 0.18) and in the standard form TS (dB) = 20 log [length (cm)] – 68.11 (95% CI -68.7 to -67.5; R^2 = 0.18).

Four fish were measured at tilt angles ranging from -50° to 70° from dorsal aspect (3 fish were measured at more than one angle). TS at the various tilt angles was standardized and expressed as a deviation from the median TS at 0° for each fish. The median was chosen as descriptive of the central tendency since it is less affected by extreme values than the arithmetic mean. Extreme values did occur for some fish that were sporadically jerking against the net. The maximum deviation of TS from the median at dorsal aspect (0°) was -3.8 dB over the range of tilt angles from -50° to 70° (Fig. 3.7).

3.6 Discussion

Useful acoustic measures of fish can be made under experimental conditions only if fish are in excellent condition. Swimbladder inflation should approximate that of free-swimming fish, and behavior should be as natural as possible. Achieving those conditions with Sebastes is difficult. However, the methods developed in this study have by and large met these conditions. In particular, fish were captured in relatively shallow waters, handling time at the surface was minimal, and the experimental set-up was installed close to the capture site. Fish that survived the capture and caging procedure appeared to be in excellent condition, and were vigorous and neutrally buoyant (no abnormal sinking or floating). Dissected swimbladders of experimental fish appeared to be normal and inflated. Some of these fish had overly inflated swimbladders at time of capture. Nevertheless, it appears that the swimbladder can deflate to a normal condition if it is not ruptured and fish are submerged to depths and pressure near those of their capture location with minimal delay. It is noteworthy that even though the fish in the best condition were used in the experiments, several others kept for four days were released at the end of the study and appeared to be in good condition.

The redfish measured were all of a similar size, with lengths of 24.5 to 30 cm. The overall mean TS of these fish at normal swimming aspect was -39.3 dB. The minimal length range of these fish predictably limited the precision of the length based model. Nevertheless, the standard TS-length model had an intercept of -68.1, which was similar to the intercept (-67.6) measured for these species in a study based exclusively on

in situ data (Gauthier and Rose, 1998), and is in good agreement with the standard reference intercept of -67.5 provided by Foote (1997) for the TS of physoclists. There are few other studies on the TS of *Sebastes* for comparison to these results. Foote et al. (1986) derived a standard form equation with an intercept of -67.1 for in-situ measurements on *Sebastes marinus* of 6 - 43 cm length in the Norwegian sea, which is similar to the present results and those of Gauthier and Rose (1998). In contrast, Reynisson (1992) reported a mean TS of -40 dB for *Sebastes mentella* of mean length 36.9 cm in the Icelandic acoustic surveying of the Irmenger sea, which is more than 3 dB lower than would be predicted by extrapolating the present data (-36.8 dB). However, the tilt angle distribution of the surveyed fish is unknown, and the difference between the results reported by Reynisson (1992) and other may relate to variability in the tilt angle distribution of free-swimming fish.

The data indicated that significant change occurred in TS with change in tilt angle. However, the amplitude of the observed directivity (to 4 dB) was not as large as reported for other species (eg. Atlantic cod) which may have directivities of 10-20 dB at similar angles (eg. Nakken and Olsen, 1977; MacLennan *et al.*, 1990; Rose and Porter, 1996). The variation in TS according to orientation will depend on the geometry of the swimbladder and on the acoustic frequency (McClatchie et al., 1996). The swimbladder of *Sebastes* is large and has a broad pear shape, in contrast to the more oblong configuration of bladders of many other species such as the gadoids (Fänge, 1953, Fig. 3.2). The inclination of the bladder longitudinal axis relative to the horrizontal plane of

the fish also has an important effect on TS (Midttun and Naken, 1971, Love, 1977; Foote, 1980b). For the redfish in this study an inclination of approximately 15° was found, as opposed to typical values of 4° to 7° for cod (Midttun and Hoff, 1962; Nakken and Olsen 1977), although Clay and Horne (1994) reported values as high as 17° for smaller cod (< 20 mm).

The relatively small variation in TS with tilt angle observed in redfish is consistent with the spherical shape of their bladder. An examination of the echotrace of single redfish suggests that they differ from those of species having an elongated swimbladder, eg Atlantic cod (Fig. 3.8). The gradient of echo amplitude is steep in cod (>20 dB). In addition cod typically have a double-tailed "inverted v" shaped echotrace with maximum intensity towards the center (as a result of directivity). In contrast, the gradient of intensity across a typical redfish echotrace is much less steep, and may be less symmetrical. These characteristics are consistent with the pear-shape reflecting surface of *Sebastes* swimbladders and could prove to be valuable in species identification based on echo signature analysis (eg. LeFeuvre *et al.* 2000). Echo-trace analysis (Furusawa and Miyanohana, 1998) and target tracking techniques (Brede et al., 1990) could be used to determine inter-specific variability in the directivity of fish by analysing the shape of the trace. Finally, the lower level of directivity suggests that variation in TS resulting from tilt angle differences may be less for *Sebastes* than for species with elongated swimbladders.

3.7 Acknowledgements

I thank the crew of the CCGS Shamook, Dennis Ivany, Wade Hiscock and Michael Norris for their assistance in the field, and John Wheeler for loan of the compound platforms. Comments by Egil Ona and an anonymous reviewer improved the manuscript. Funding came from the Canada Department of Fisheries and Oceans (Redfish Multidisciplinary Research Program) and the Natural Sciences and Engeneering Research Council of Canada Industrial Chair in Fisheries Conservation.

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3.9 Figures

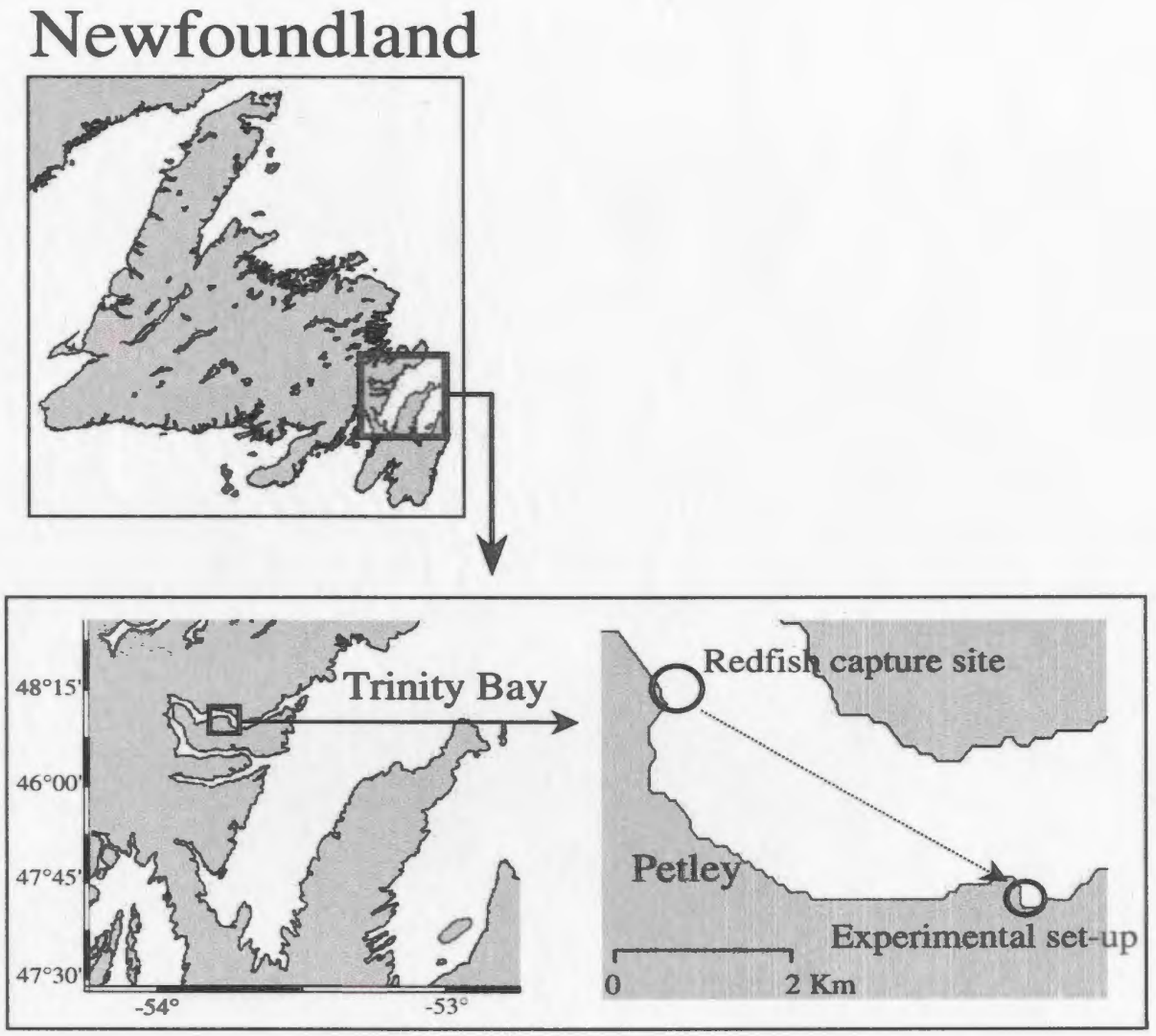


Figure 3.1. Location of the capture and experimental site in Trinity Bay, Newfoundland, Canada.

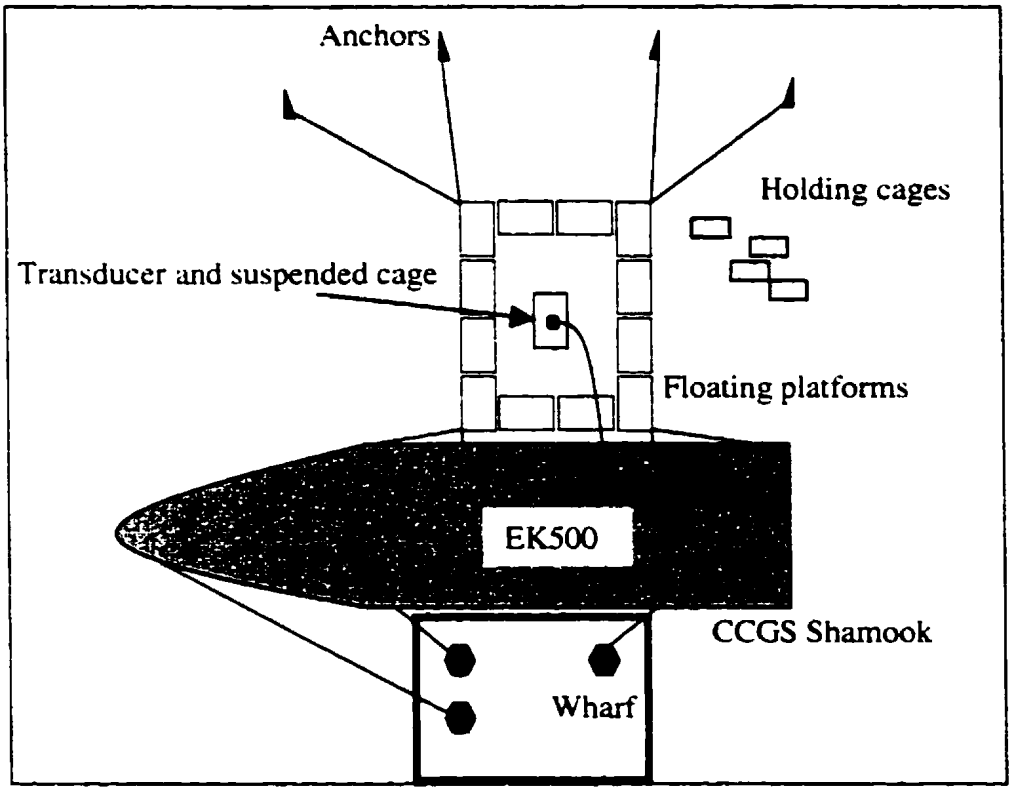


Figure 3.2. Aerial view of the experimental compound set-up for TS measurements.

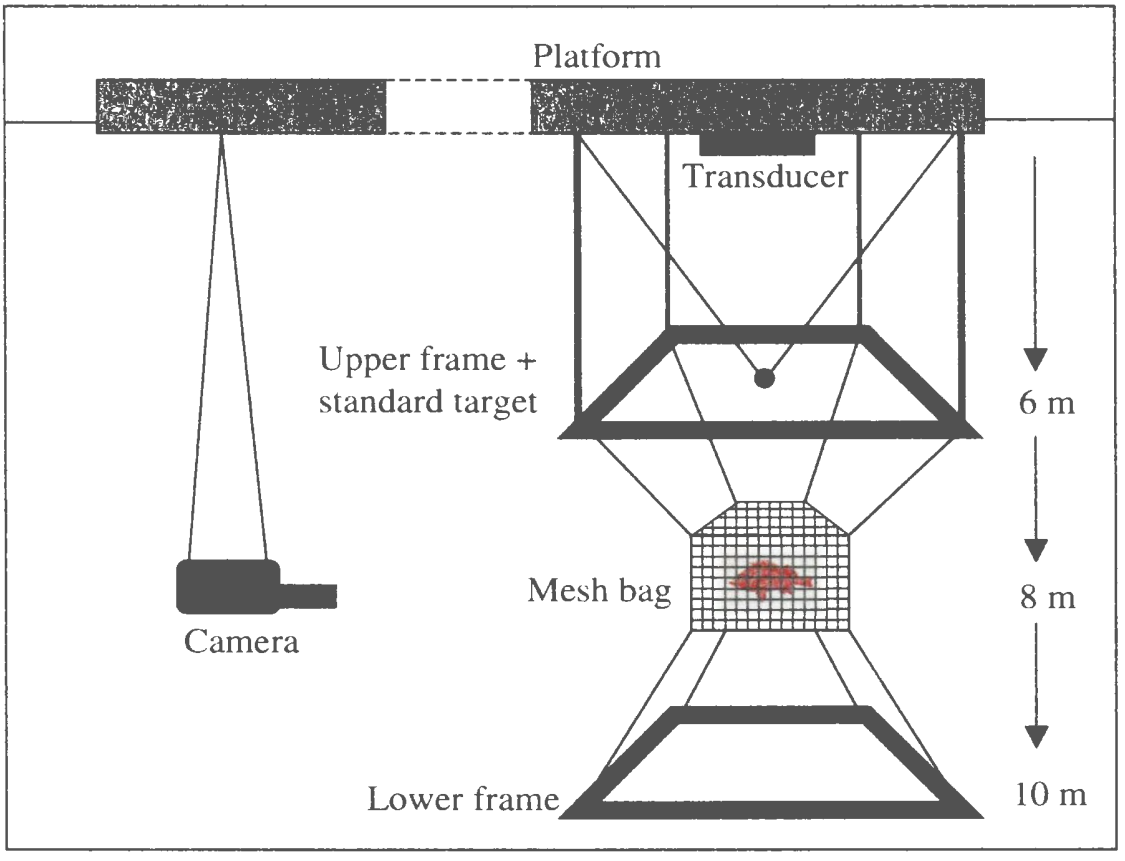


Figure 3.3. Apparatus for target strength measurements. The upper and lower stretching frames were 2.5 m squares and were constructed of 2.5 cm aluminum tubing. The mesh bag was made of light monofilament and was acoustically invisible at a threshold of –70 dB. The camera was a low-light black and white video with surface monitor.

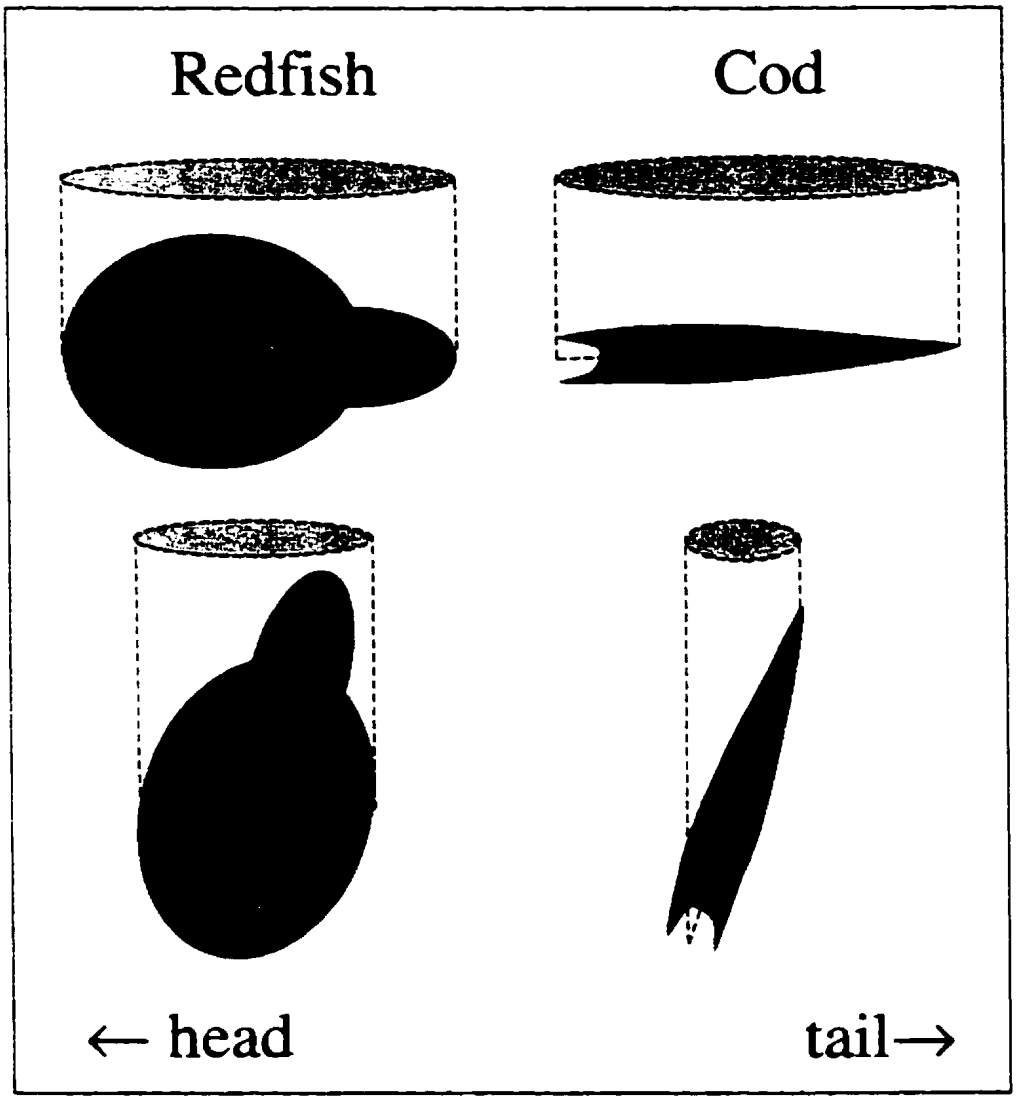


Figure 3.4. Variation of the cross sectional area at maximum dorsal aspect and -70° tilt angle for swimbladders of redfish (*Sebastes*) and cod (*Gadus*) of the same length. Shapes roughly reproduced from Fänge (1953). Maximum dorsal aspect for redfish is equivalent to a 15° downward inclination of the head to tail axis. This angle is between 4° and 7° for cod.

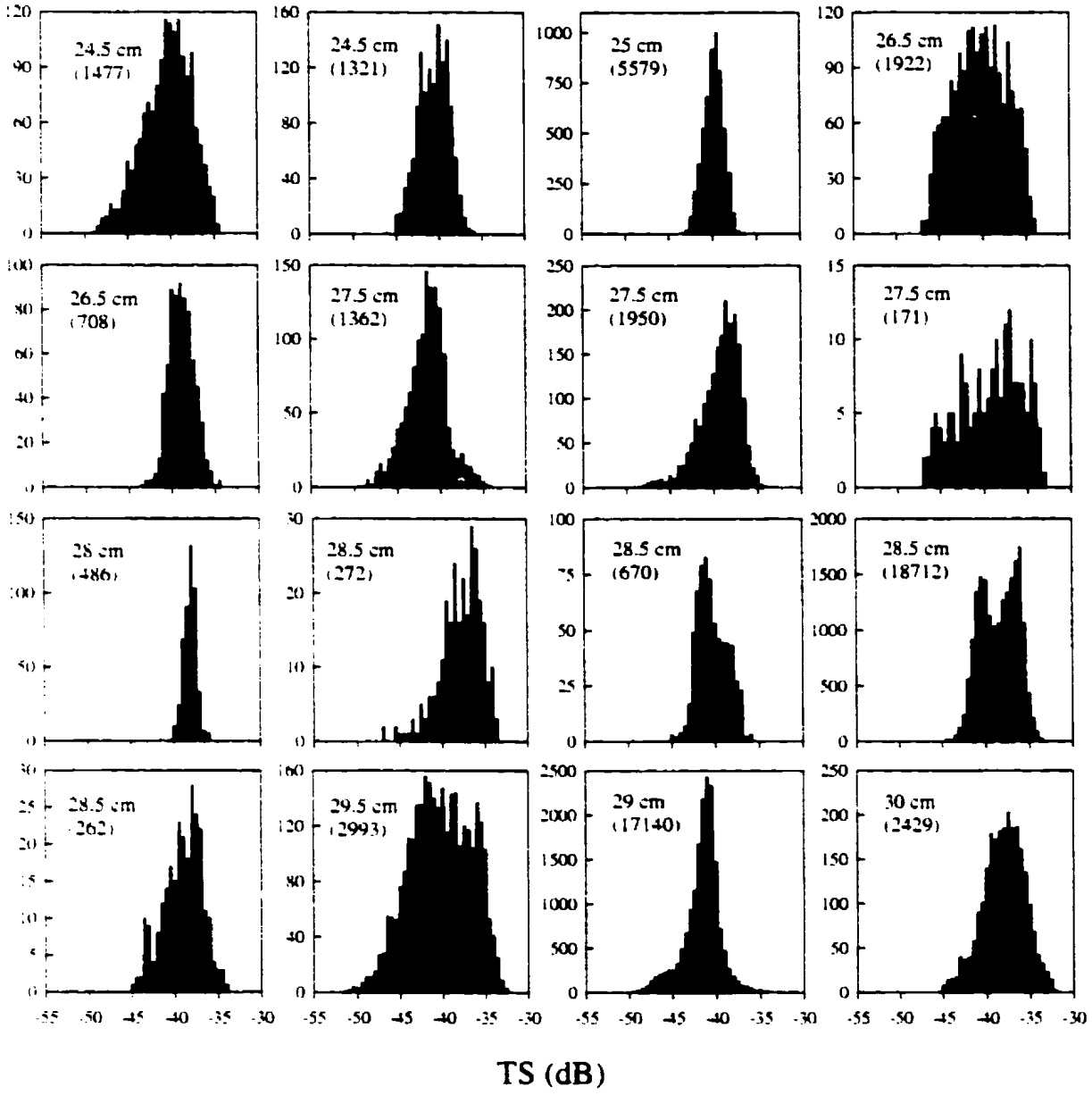


Figure 3.5. Target strength frequency histograms for the 16 redfish measured. Length (cm) and sample size (N = number of pings) are given for each individual.

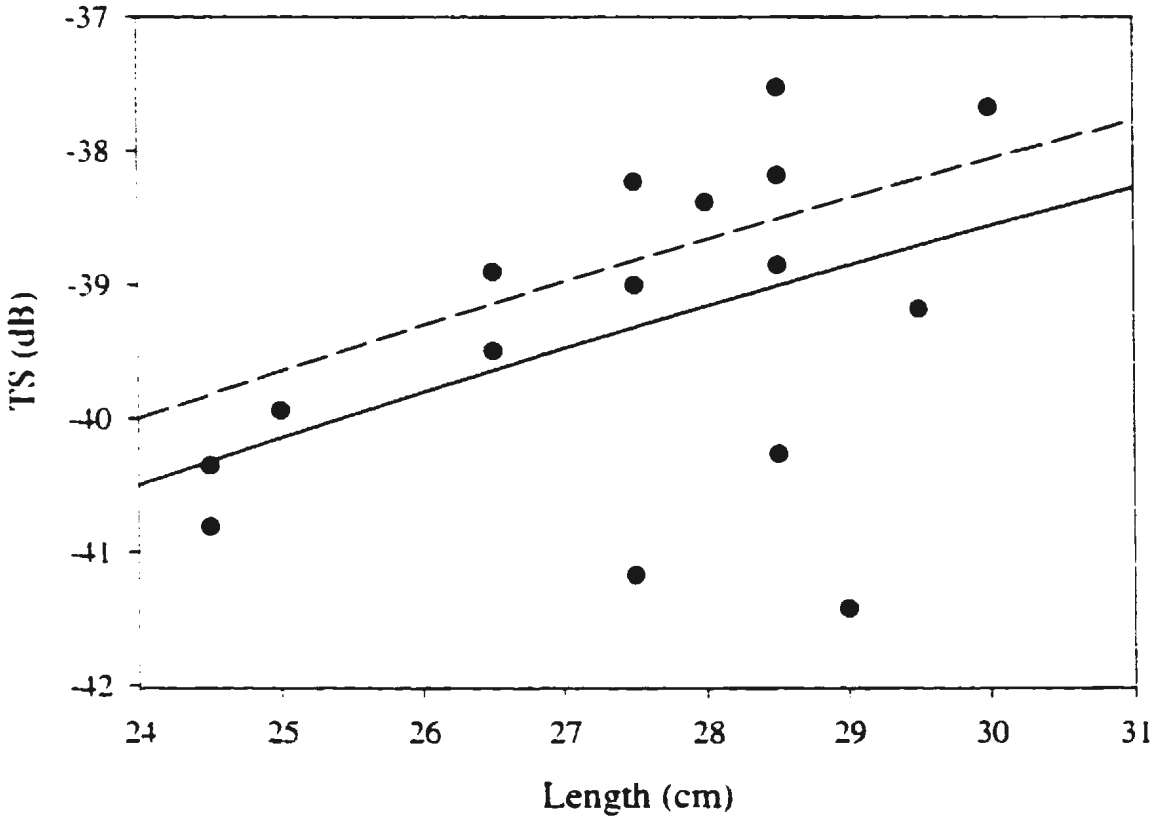


Figure 3.6. Mean target strength (TS) of redfish with respect to length. The straight line represents TS (dB) = 20 log [length (cm)] – 68.1 (this study) while the doted line represents TS (dB) = 20 log [length (cm)] – 67.6 (Gauthier and Rose, 1998).

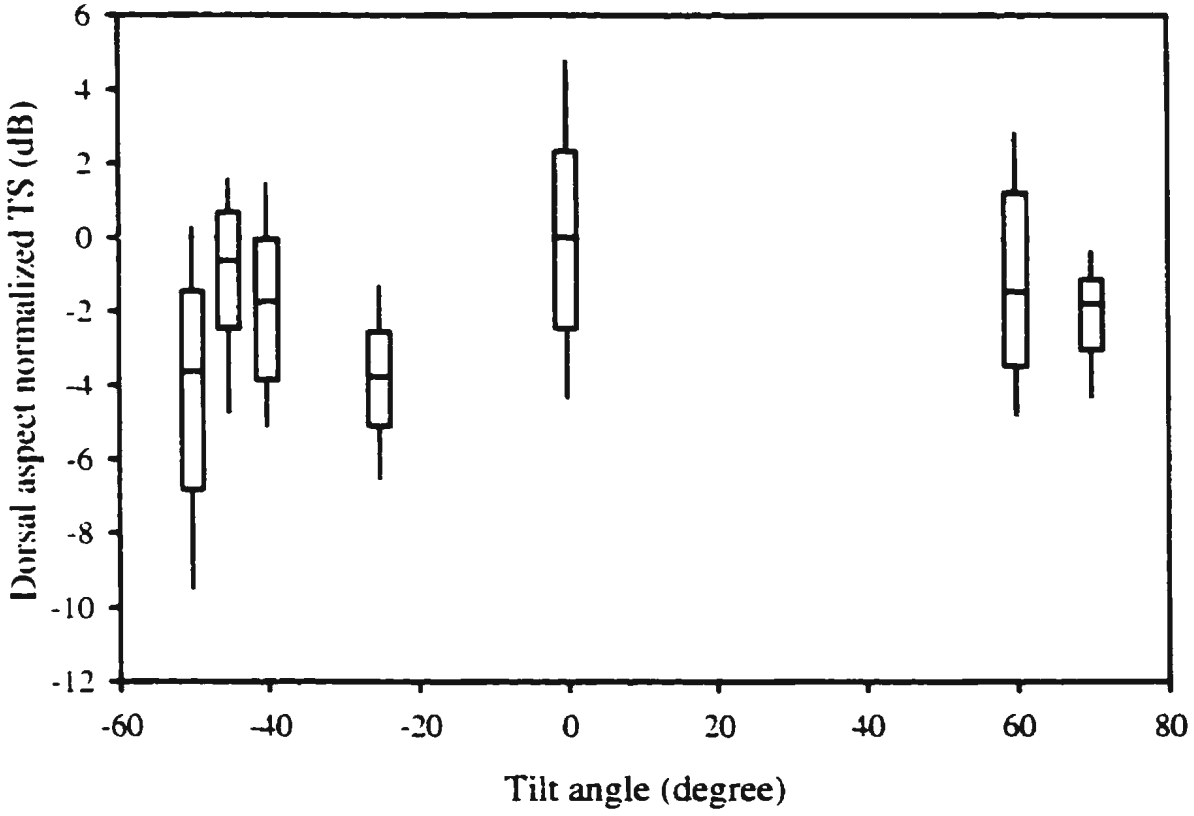
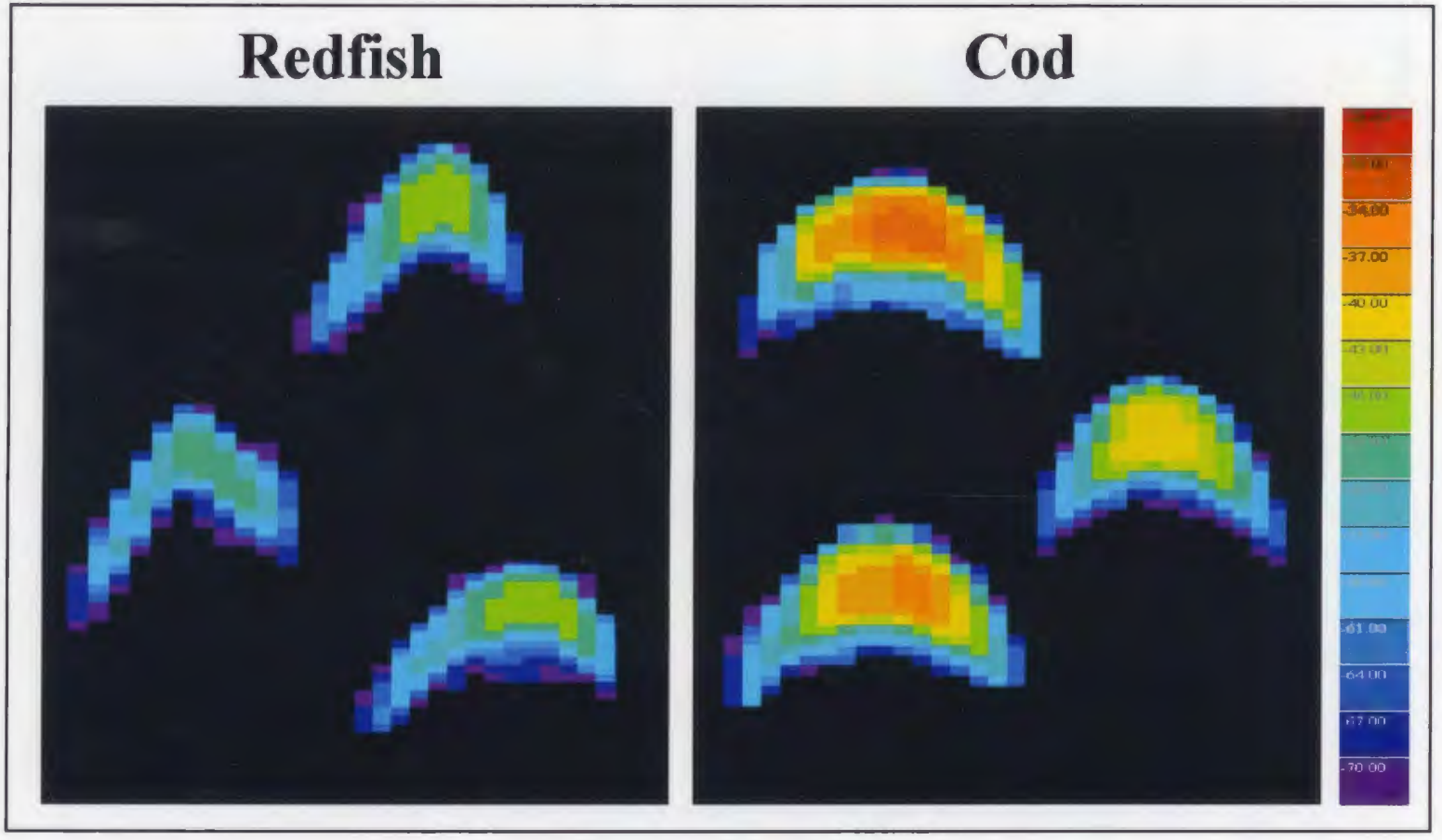


Figure 3.7. Variation of normalized dorsal aspect target strength (TS) with tilt angle for 4 different individuals. Boxes represent median TS with 75th and 25th percentiles. Vertical bars represent the 90th and 10th percentiles.

Figure 3.8. Typical echotraces of single redfish (*Sebastes mentella*) and Atlantic cod (*Gadus morhua*) at 40logR amplification. Traces were formed by 11-16 adjacent echoes received as the acoustic beam passed over the fish. Traces were collected under similar conditions using an EK500 38 kHz split-beam transducer. A relative color scale is shown on the right, with steps of 3 dB.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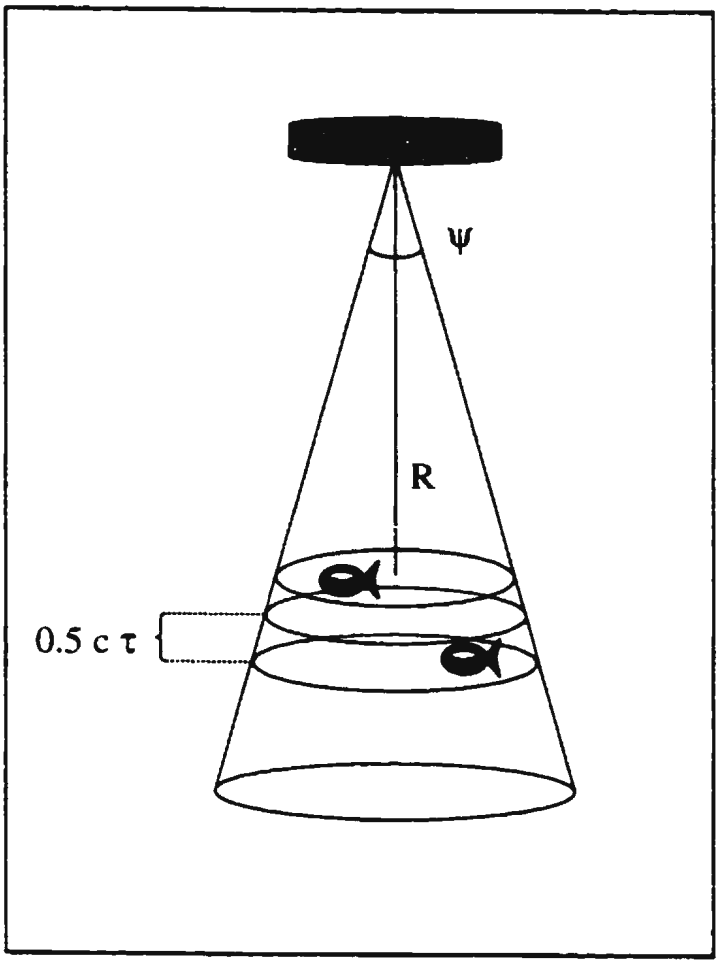
Chapter 4. Diagnostic tools for unbiased *in situ* target strength estimation



4.1 Abstract

In situ target strength (TS) is theoretically the optimal measure to scale echo-integration values to fish density. In practice, *in situ* TS is often biased. The number of fish relative to 1 sample volume (N_v) has been used to set a threshold density to reduce the bias attributable to multiple targets. However, order of magnitude differences in the N_v threshold have been reported within the theoretical range $0 < N_v \leq 1$. To investigate the use and scale-dependence of the N_v index, with the objective of achieving unbiased estimates of *in situ* TS, redfish (*Sebastes spp.*) aggregations were measured in Newfoundland waters. When averaged over large horizontal distances (large scale), TS was biased upwards if N_v exceeded 0.04. However, TS could be estimated at higher densities without bias using smaller measurement scales. To deal with these scale-dependent variations, we develop diagnostic tools based on N_v and an echo-count index (NT_v) which enable more accurate estimates of the N_v threshold and *in situ* TS.

4.2 Résumé

En théorie, l'indice de réflexion (IR) estimé *in situ* est la mesure optimale pour transformer les valeurs d'écho-intégration acoustique en densité de poissons. En pratique, les mesures *in situ* de l'IR sont souvent biaisées. Le nombre de poissons par volume échantillonné (N_v) à été utilisé pour déterminer un seuil de densité permettant de réduire le biais associé aux cibles multiples. Cependant des différences jusqu'à un ordre de grandeur ont été rapportées pour la valeur limite de N_v à l'intérieur de sa distribution théorique $0 < N_v \leq 1$. Dans le but d'obtenir des estimations non-biaisées de l'IR, j'ai examiné la validité de N_v et sa dépendance avec l'échelle spatiale pour des agrégations de sébastes (*Sebastes spp.*) dans les eaux de Terre-Neuve. A des mesures prisent à grandes échelles, l'IR était positivement biaisé quand les valeurs de N_v étaient > 0.04. Cependant, des densités beaucoup plus élevées pouvaient être mesurées sans biais à des échelles spatiales plus petites. Pour adresser ces variations, j'ai développé des outils diagnostiques basés sur N_v et sur un index du nombre d'échoes (T_v) qui permettent une estimation non biaisée du seuil limite de N_v et de l'IR *in situ*.

4.3 Introduction

An unbiased estimation of acoustic target strength (TS) *in situ* is theoretically the optimal measure to scale acoustic backscatter to fish density (Rose, 1992). Using current technology, unbiased measures of TS can seldom be determined *in situ* because reverberation volumes are most often too large to allow isolation of single targets, and signal filters used to identify single targets are imperfect (Foote, 1994; Soule et al., 1995).

A low fish density has long been thought necessary to correctly identify echoes from single targets, and hence to make unbiased measurements of *in situ* TS (eg. Traynor, 1984). In addition to the various pulse shape criteria for identifying single targets, several approaches have been used in attempts to limit bias resulting from the inclusion of composite signals from more than one fish, so-called multiple targets, as single targets. For example, Foote et al. (1986) applied additional pre-processing to accept as single targets only echoes that had at least four zero-coded measures before and after the target of interest (in their system, TS values were represented in coded form following analog-to-digital conversion). Consequently, accepted targets were separated by more than one pulse duration. A decade later, Barange et al. (1996) used additional post-processing to identify likely multiple echoes of anchovy (*Eugraulis capensis*), by assuming log-normal distribution of backscattering cross-sections and fitting a one-tailed normal function to the portion of the TS distribution attributed to single targets. Simulations using the mean and standard deviation of the filtered distribution were then employed to estimate the mean backscatter. Improvements in single target isolation methods have also been

proposed (Soule et al., 1996; Demer et al., 1999). However, such methods may require methodological approaches that are impractical (eg. simultaneous use of two split-beam systems).

The general approach to resolving these problems has been to avoid using *in situ* TS measures to scale integrated backscatter if densities surpass some empirically determined threshold. Sawada et al. (1993) showed that density measured as the number of fish in 1 acoustic reverberation volume (N_v) can be determined as:

(1) $$N_v = \frac{c\tau\psi R^2 n_{EI}}{2}$$

where c is the speed of sound in water in $m \cdot s^{-1}$, τ is the transmit pulse duration in s, ψ is the equivalent beam angle in steradians, R is the target range in m and n_{EI} is the volumetric fish density in $fish \cdot m^{-3}$, determined from volume scattering coefficient (S_v) and TS estimates determined from the length distribution and applied to a TS – length model. In theory, multiple targets should be excluded if fish are homogeneously distributed (equidistant spacing between consecutive fish) and N_v does not exceed 1 fish. However, fish are seldom homogeneously distributed, and empirical evidence has suggested that in practice a much lower threshold should be employed (Sawada et al., 1993). The N_v index has been used to set a density threshold for TS estimates in several studies (e.g. Barange et al., 1996; Rose, 1998; Rudstam et al., 1999).

An inspection of N_v values found in the literature suggests a relationship between threshold values and fish size (Table 1). The mechanism by which such a relationship might exist is unclear. Fish size could affect the volume calculation by influencing the minimum distance between targets required for discrimination. However, at frequencies used in fisheries acoustics (10–200 kHz), gas filled bodies (swimbladders) have dimensions that are small relative to acoustic wavelengths (Clay, 1992), and reflected energy from the far side of the swimbladder is negligible compared to reflection near its surface (Clay and Horne, 1994). Consequently, fish with swimbladders can be considered to be point scatterers, and fish size is unlikely to significantly influence the vertical dimension of the reverberation volume. Therefore, the discrepancies in threshold values found in the literature are more likely to result from other factors. Fish densities used to estimate the N_v index are determined by volume scattering coefficients (S_v). Hence, N_v is subject to the same sources of variance that affect TS, including the effect of system threshold, the scaling of acoustic backscatter to actual fish size, and the orientation distribution of fish (Foote, 1980). Moreover, measurement range, signal to noise ratio conditions and sum-beam threshold are dependant on fish size and can alternatively affect sampling volume, and hence N_v measurements (Kieser and Mulligan, 1984; Crittenden *et al.*, 1988). Another potential source of variance is the scale at which measurements have been made, especially in the larger horizontal dimension.

In this paper I propose a theoretical relationship between the N_v index, TS bias, and horizontal measurement scale. I examine empirical estimations of the N_v threshold

from the literature and original research on Atlantic redfish (*Sebastes spp.*). I test the effect of horizontal measurement scale on fish densities and the determination of an appropriate N_v threshold. Finally, I recommend a suite of diagnostic tools to diagnose and improve the reliability of *in situ* TS estimations.

4.4 Material and methods

4.4.1 N_v threshold

Four large aggregations of redfish (*Sebastes spp.*) were acoustically sampled on the edge of the Grand Banks of Newfoundland in July 1996 and January 1997 using a 38 kHz purpose-built dual-beam echosounder operated from the Canadian Coast Guard Vessel "Teleost" (64 m research trawler). The transducer (half power angles of 7° and 14° for the narrow and wide beam, respectively) was mounted in a towed body with 400 m of multi-channel armored tow cable. Transects were defined over each aggregation and the towed body was deployed at depths from 50-300 m from the surface in multiple passes along each transect. This approach enabled us to measure the TS of redfish over a wide range of acoustic densities and ensonified volumes.

The echosounder was calibrated with a 38.1 mm tungsten-carbide sphere using procedures recommended by Foote et al. (1987). Standard dual beam techniques were used to determine TS (Iida et al., 1991). Signals were filtered to reject pulses narrower than the 0.8 ms transmission pulse and wider than 1.2, 1.5, and 1.8 times the pulse width

at the half, quarter and eighth heights of the pulse (Traynor and Ehrenberg, 1979). Data were also rejected if the ratio of the width at the half to quarter heights and the quarter to eighth heights was below 0.75 or above 1. These relatively strict pulse criteria were chosen to minimize the inclusion of echoes from overlapping targets (MacLennan and Simmonds, 1992). Target strength was arithmetically averaged from the backscattering cross sections prior to logarithmic transformation (Foote, 1987). The number of fish per effective reverberation volume was calculated using equation 1. The volumetric fish density was calculated for bins of 10 m depth by 300-500 pings (800-1400 m) using volume scattering coefficients (S_v) and TS estimated from catch data and TS-length models for redfish (Gauthier and Rose, 1998).

In theory, the N_v threshold at any given scale of observation should correspond to the mean at which maximum values exceed 1 fish per sample volume, assuming an unbiased estimate of fish density (Fig. 4.1). To examine the effect of horizontal measurement scale on threshold value, the mean and maximum N_v were measured in all redfish aggregations at intervals of 500, 100, 20, and 10 pings (1 ping ~ 2.8 m). The sampling rate was kept constant throughout the study (same boat speed and ping interval), hence the number of pings represents distance.

4.4.2 Diagnostics for N_v and TS

A new index to estimate the reliability of N_v estimates is introduced. This index is the number of targets in 1 reverberation volume:

(2) $$T_v = \frac{c\tau\psi R^2 n_{EC}}{2}$$

Where n_{EC} is the absolute volumetric target density, calculated as:

(3) $$n_{EC} = \frac{\overline{N}_\Omega}{V_\Omega}$$

where N_Ω and V_Ω are the mean number of targets per ping and the volume at the cutoff angle Ω. The mean number of targets per ping was calculated by dividing the total number of returned echoes (inside a cutoff angle) by the number of pings. Volume for a 10 m depth layer was calculated using the geometric equation for a cone at range R and range R – 10 m:

(4) $$V_\Omega = \left(\frac{\pi a_R^2 R}{3}\right) - \left(\frac{\pi a_{R-10}^2 (R-10)}{3}\right)$$

where a_R and a_{R-10} are the radii of the cones at the base in m, calculated as:

(5) $$a_R = R \cdot \tan\Omega$$

In this study, I used a cutoff angle of 3.24° for the narrow beam (corresponding to -3 dB off axis), and 10 m depth layers. I chose a -3 dB off-axis position for echo-counting as it corresponds to the parameter used for single target detection. The echo-counting approach is subject to many sources of error induced by beam attenuation and threshold effects, all of which increase with larger angles (Nunnallee, 1980; Kieser and Ehrenberg, 1990). The average number of targets per ping was measured for bins of 300-500 pings (same vertical and horizontal scaling as for N_v). In theory, the number of targets in a reverberation volume (T_v) should be the same as the number of fish in a reverberation volume (N_v) until target density becomes sufficiently high so that multiple echoes are produced. The inflection point of T_v on N_v should appear at (or shortly before) the threshold value of N_v (Fig. 4.2). In this basic representation, the other sources of error mentioned above were ignored. Stochastic models of fish distribution also indicate a sharp drop in echo-counting values as fish relative density increases above a certain level (Ehrenberg and Lytle 1972). The shape of the curve beyond the inflection point and the magnitude of the difference between this inflection point and the threshold value of N_v will depend on the robustness of the single target algorithm. With a perfect algorithm, the curve should drop sharply once the number of fish per sample volume exceeds 1 in every cell. However, the position of the inflection point should be robust against algorithm variation.

If the TS estimate used in the N_v calculation is biased, the slope of N_v against T_v will differ from 1. Bias may also result from contamination of other species having a

different TS distribution. These potential biases can be detected by comparison of the two indices (N_v and T_v).

4.5 Results

4.5.1 N_v threshold

In all 4 redfish aggregations, TS increased at N_v levels above approximately 0.04 (Fig. 4.3). This threshold density for N_v is the same as determined by Sawada et al. (1993) for walleye pollock *Theragra chalcogramma*.

Values of N_v for redfish aggregations varied significantly with the scale of measurement (Fig. 4.4). For redfish distributed between 150 m and 300 m depth, N_v values calculated over the entire horizontal scale (500 pings, i.e. ~1400 m) were less than 1 in all depth layers. However, the distribution of N_v determined on a ping-by-ping basis was highly heterogenous and often exceeded 1 fish per sample volume. Maximum N_v values were as high as 2.7 fish and were 1.6 - 18 times the mean in the various depth layers. Averaging the distance affected the measured mean density because of high local variance in fish distribution.

At a horizontal scale of 500 pings (~1400 m), maximum N_v exceeded 1 fish at a mean of approximately 0.04 (Fig. 4.5 a). However, as the measurement scale decreased, the threshold value increased (Fig. 4.5 b - d). At a scale of 100 pings (~280 m), maximum

Nv exceeded 1 fish at a mean above 0.06 fish. For scales of 20 and 10 pings (~56 m and ~28 m) the corresponding values were, respectively, 0.2 fish and 0.4 fish.

4.5.2 Diagnostic for N_v and TS values

For redfish data averaged over long distances (500 pings, ~1400 m), the point of inflection where the number of targets in 1 sample volume (T_v) decreased to values less than N_v occured at (or shortly before) the threshold value independently determined for N_v (Fig. 4.6). Simulated errors in assumed TS caused bias in N_v values. When TS was set too low, the slope was > 1 below the inflection point. When TS was set too high, the slope was < 1.

The inclusion of non-specified echoes with the target echoes could also influence the relationship between T_v and N_v. In an attempt to distinguish between biases attributable to non-specified echoes and TS, we examined acoustic data from redfish known to be mixed with euphausiids based on mid-water trawling. Euphausiids are relatively small acoustic targets (TS between -80 to -90 dB for Antarctic krill measured at 38 kHz, Everson et al. 1990) and individuals are unlikely to be detectable at the ranges and with the system used in this study. Moreover, large acoustic reverberation volumes increase the probability that multiple echoes will pass the single target criteria. The mixed data contained many TS measured in the -50 to -65 dB range, especially where euphausiids were found in dense layers. Multi-species TS data were typically bimodal, in contrast to monospecific redfish TS data, which were typically unimodal (Fig. 4.7).

Mixed data exhibited T_v values that exceeded N_v, resulting in a T_v / N_v slope > 1. For all cases where the two TS modes were distinguishable and the lower mode was excised, the resultant T_v did not differ from N_v (Fig. 4.8).

4.6 Discussion

Analysis indicated that bias in redfish TS occurred above N_v values of 0.04 for data averaged over an horizontal scale of 500 pings (~1400 m). This threshold corresponded to the mean N_v at which maximum N_v values exceeded 1 fish in a sampling volume. My analysis also indicated that changing the horizontal measurement scale can result in order of magnitude differences in the N_v threshold required to limit TS bias caused by the inclusion of multiple targets. This finding may explain the wide variety of N_v values used in previous studies. For example, in their study of juvenile capelin (*Mallotus villotus*) of mean length 5 cm, O'Driscoll and Rose (2001) used an N_v threshold 10 times higher (N_v = 0.4) than in our study of redfish and that of Sawada et al. (1993) of walleye pollock. The horizontal averaging distance employed by O'Driscoll and Rose (2001) was 50-100 m and much smaller than in other studies. Sawada et al. (1993) employed a distance of at least 700 m. Barange et al. (1996), in their assessment of Pilchard (*Sardinops ocellatus*), reported maximum densities of < 0.5 targets per sample volume over distances of approximately 1500 m, but exceeding two targets per volume over smaller distances (25 pings, no distance given). Rose (1998) showed that maximum densities typically exceed mean densities by an order of magnitude in capelin (*Mallotus villosus*) if horizontal averaging distances are large. In general, averaging

undertaken over larger distances will necessitate a lower threshold N_v to counteract the increasing likelihood of including multiple targets. Since S_v (and hence N_v) is typically averaged over 100 pings or more, thresholds set empirically are likely to be much lower than the theoretical value of unity.

In my analyses, vertical bins where kept constant at 10 m depth. However a similar scale dependence may apply to the vertical dimension. Reverberation volumes have a thickness of $0.5c\tau$, which is equal to approximately 0.6 m with our system. Hence, approximately 16 reverberation volumes are averaged over 10 m in one ping. Vertical averaging may also impact the N_v threshold as a consequence of the likelihood of having one or more values exceeding unity within a density averaged depth bin. I chose to use relatively small 10 m bins to simplify calculations and keep vertical bias minor relative to the bias observed at much larger horizontal scales. It is noteworthy that the N_v value above which TS becomes biased will depend on the accuracy of the single target isolation criteria. Very strict isolation criteria were used in this study to maximize the N_v at which TS was unbiased.

Sawada et al. (1993) compared the number of echoes with fish density to calculate the percentage of multiple targets. The measured fish density was assumed to be unbiased with respect to TS. The comparison of T_v and N_v index is more robust against variations in single echo isolation performance and errors in TS. The T_v will be lower than the N_v when significant numbers of multiple echoes occur, irrespective of whether these echoes

are accepted or rejected by the isolation algorithm. The inflection point of the $T_v - N_v$ plot occurs at the density threshold above which multiple targets are included. The threshold of the N_v – TS plot may be slightly higher than the inflection point of the $T_v - N_v$ plot, as a consequence of efficient single isolation algorithms. Hence, $T_v - N_v$ comparison is likely to indicate N_v threshold that will eliminate multiple target bias in *in situ* TS data.

The slope of the $T_v - N_v$ plot near the origin should be unity if the assumed TS is unbiased. A slope that differs from unity indicates either that the assumed TS is biased, or that multiple types of targets comprise part of the data. These types of biases can be distinguished by examining the frequency distribution of the TS data for multi-modality. Williamson and Traynor (1984) demonstrated that bimodality in TS for fish with a unimodal length distribution can occur if the directivity of the fish is characterized by a single, narrow, near-horizontal lobe and a tilt-angle distribution having a wide range of angles, centred near the horizontal with a singular mode. In most situations, an examination of the data should identify such cases. For example, bimodality was observed in some of our redfish data. However, because the directivity of redfish is relatively weak (Gauthier and Rose, 2001), the lower TS mode was likely too low to be redfish at tilted angles. Furthermore, an examination of well-defined single fish traces failed to show any TS bimodality. As further evidence, euphausiids were observed in the fishing sets whenever two modes were present, and filtering a portion of the echograms where the two TS modes were well separated resulted in near identical values of fish and

targets in 1 sample volume. Based on these observations, we conclude that the two modes represent two different classes of targets (single targets of redfish and multiple targets of euphausiids).

In conclusion, I propose the following steps to achieve unbiased measurement of *in situ* TS: 1) Calculate N_v and T_v and TS over as small a horizontal binning distance and as wide a range of densities as possible, using strict single target isolation methods. If measured for single pings, N_v should not exceed a value of 1, and if averaged over many pings, the N_v threshold will be < 1 and empirically determined by examining N_v – TS plots and estimating the N_v above which TS increases. In cases where N_v and T_v must be averaged over long distances, the scale should be kept as consistent as possible for comparison with other studies. 2) Plot N_v against T_v. The point of inflection (sudden reduction in T_v) should occur at or shortly before the estimated N_v threshold value. If N_v and T_v differ below the inflection point, then the TS scaling used to calculate N_v is likely biased (assuming a unimodal TS distribution). 3) If the TS distribution is not unimodal, information on the directivity and tilt-angle distribution will be required before any attempt can be made to isolate a mode representative of the targeted size group. 4) An unbiased estimate of mean TS can then be averaged arithmetically from bins whose N_v does not exceed the threshold value. 5) Finally, reports of TS should include descriptions of fish densities and methods used to select single targets.

4.7 Acknowledgements

I thank the crew of the CCGS Teleost, C. Lang and R. Forward for assistance at sea. Funding was received from the Canada Department of Fisheries and Oceans (Redfish Multidisciplinary Research Program) and the Natural Sciences and Engineering Research Council of Canada Industrial Chair in Fisheries Conservation.

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4.9 Tables

Table 4.1. Reported values of maximum N_v utilized in previous studies to limit bias in TS caused by multiple targets. Sources are: 1. This study; 2. Sawada et al. (1993); 3. Barange et al. (1996); 4. Rose (1998); 5. O'Driscoll and Rose (2000).

Species	L (cm)	N_v	Vertical bin (m)	Horizontal bin (m)	Source
Atlantic redfish	22	0.04	10	800-1400	1
Walleye pollock	18.3	0.04	4-16	700 - 1500	2
Pilchard	15.5	0.35	1	Ca. 1500	3
Capelin	12.3	0.15-3.35	10	100	4
Capelin	5.1	0.4	5	50-80	5

4.10 Figures

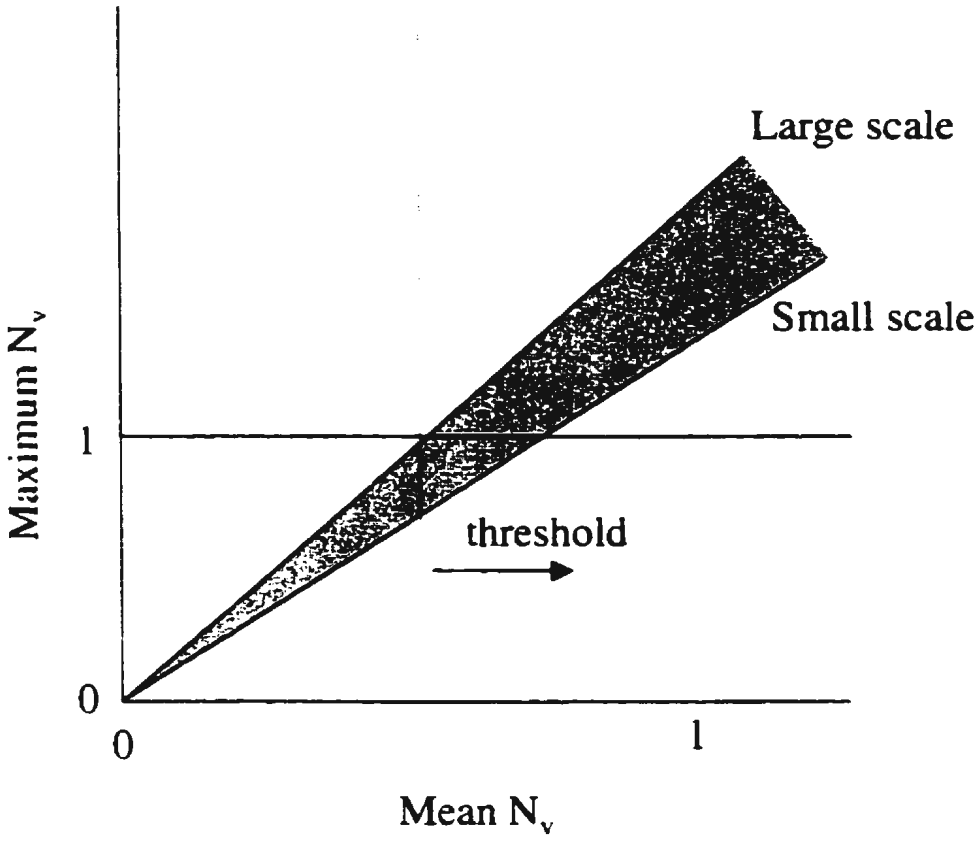


Figure 4.1. Proposed relationship between max N_v, mean N_v, and N_v threshold at different measurement scales that will exclude multiple targets.

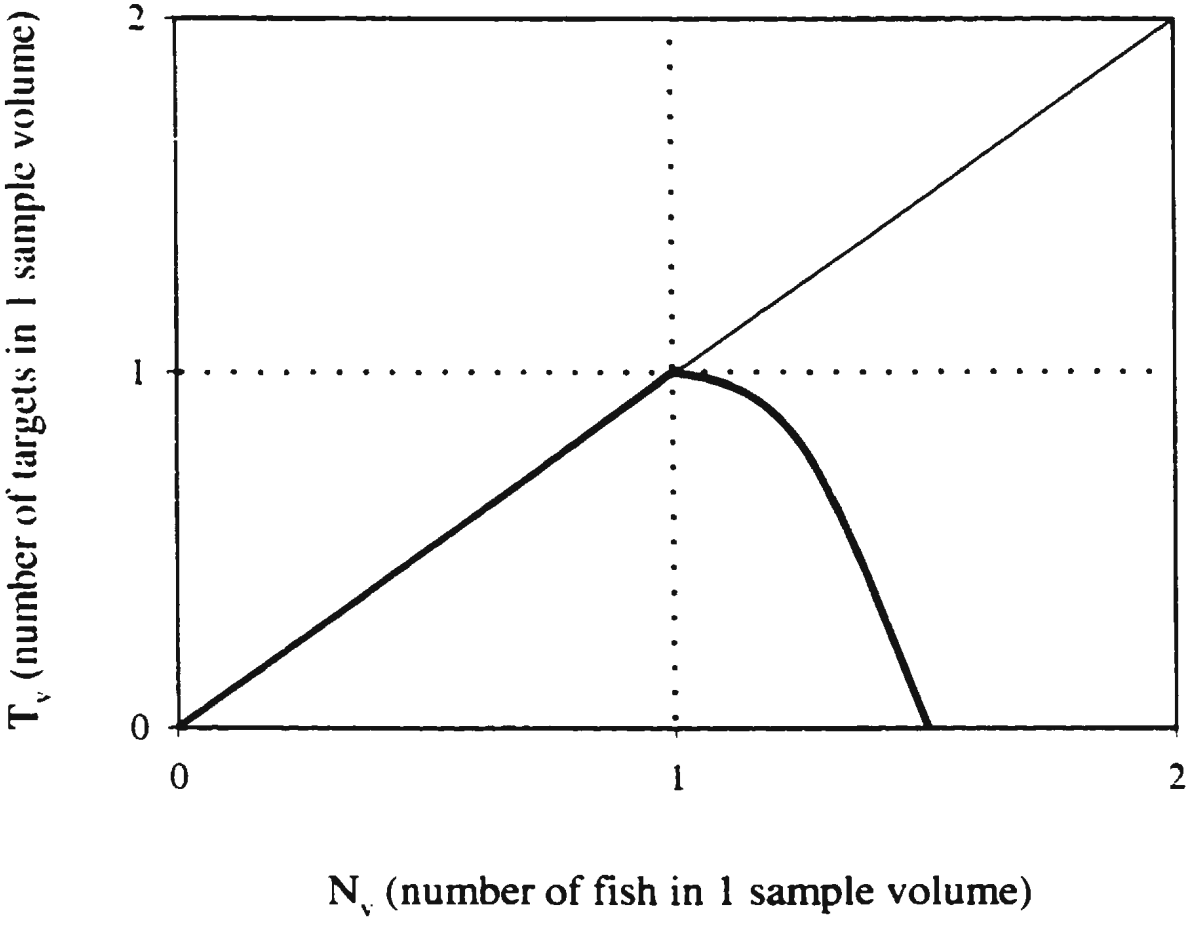
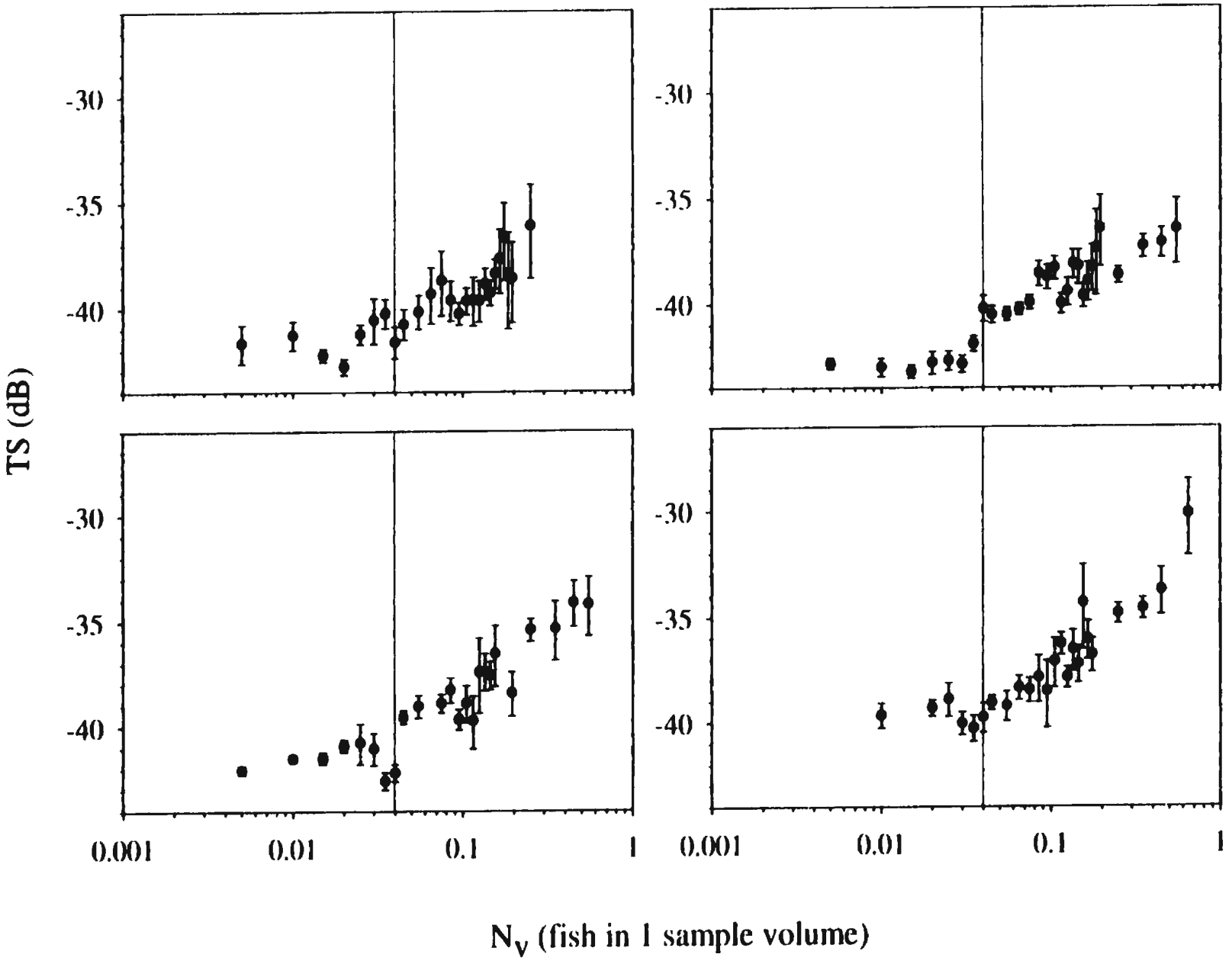


Figure 4.2. Proposed relation between the number of targets (T_v) and number of fish (N_v) in 1 sample volume.

Figure 4.3. Effect of the number of redfish in 1 sample volume (N_v) on mean target strength (± 2 standard error) at 38 kHz. The vertical lines represent threshold levels of 0.04.


TS (dB)
-30
-35
-40
0.001
0.01
0.1
1
N_V (fish in 1 sample volume)

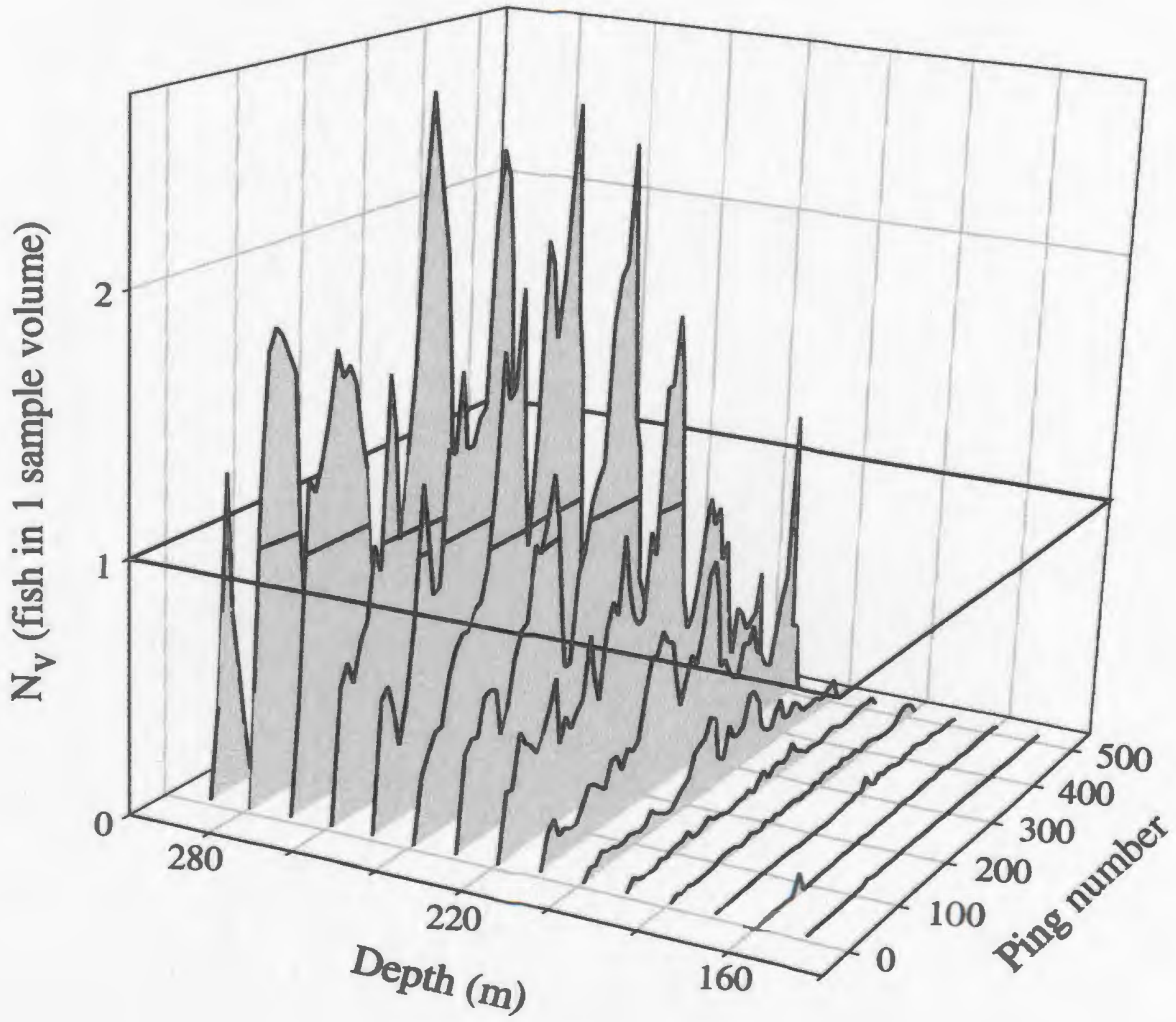
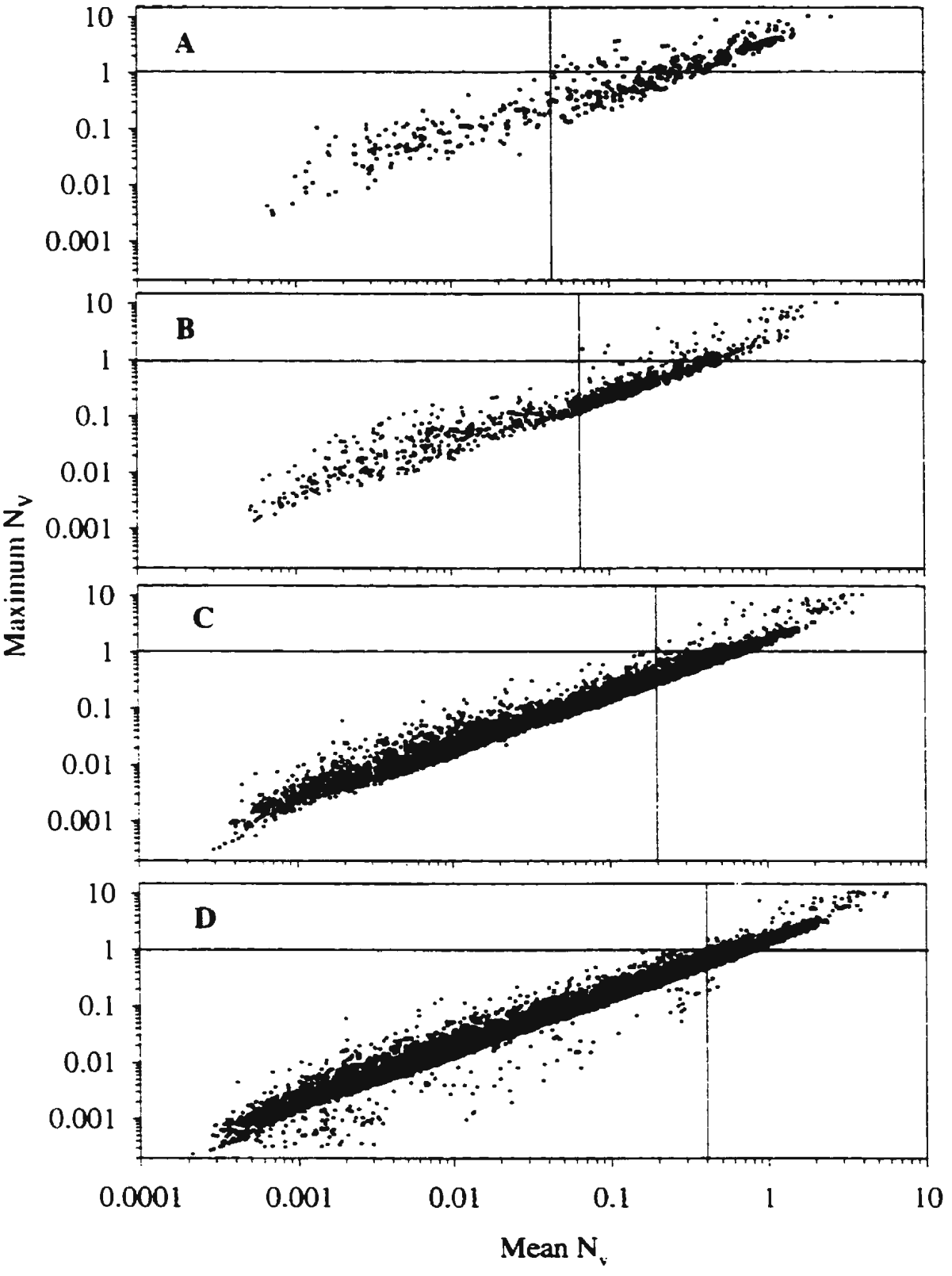


Figure 4.4. Distribution of N_v for each 10 m depth layer in an aggregation of redfish located between 150 m and 300 m depth. Values > 1 indicate potential bias in mean target strength.

Figure 4.5. Relationship between maximum and mean number of fish in 1 sample volume (N_v) at different horizontal measurement scales: a) 500 pings, b) 100 pings, c) 20 pings, and d) 10 pings (1 ping is equal approximately to 2.8 m). Horizontal bars represent the maximum theoretical N_v value of 1. Vertical bars represent the threshold value (mean at which maximum > 1).


A
B
C
D
10
1
0.1
0.01
0.001
Maximum N_v
0.0001
0.001
0.01
0.1
1
10
Mean N_v

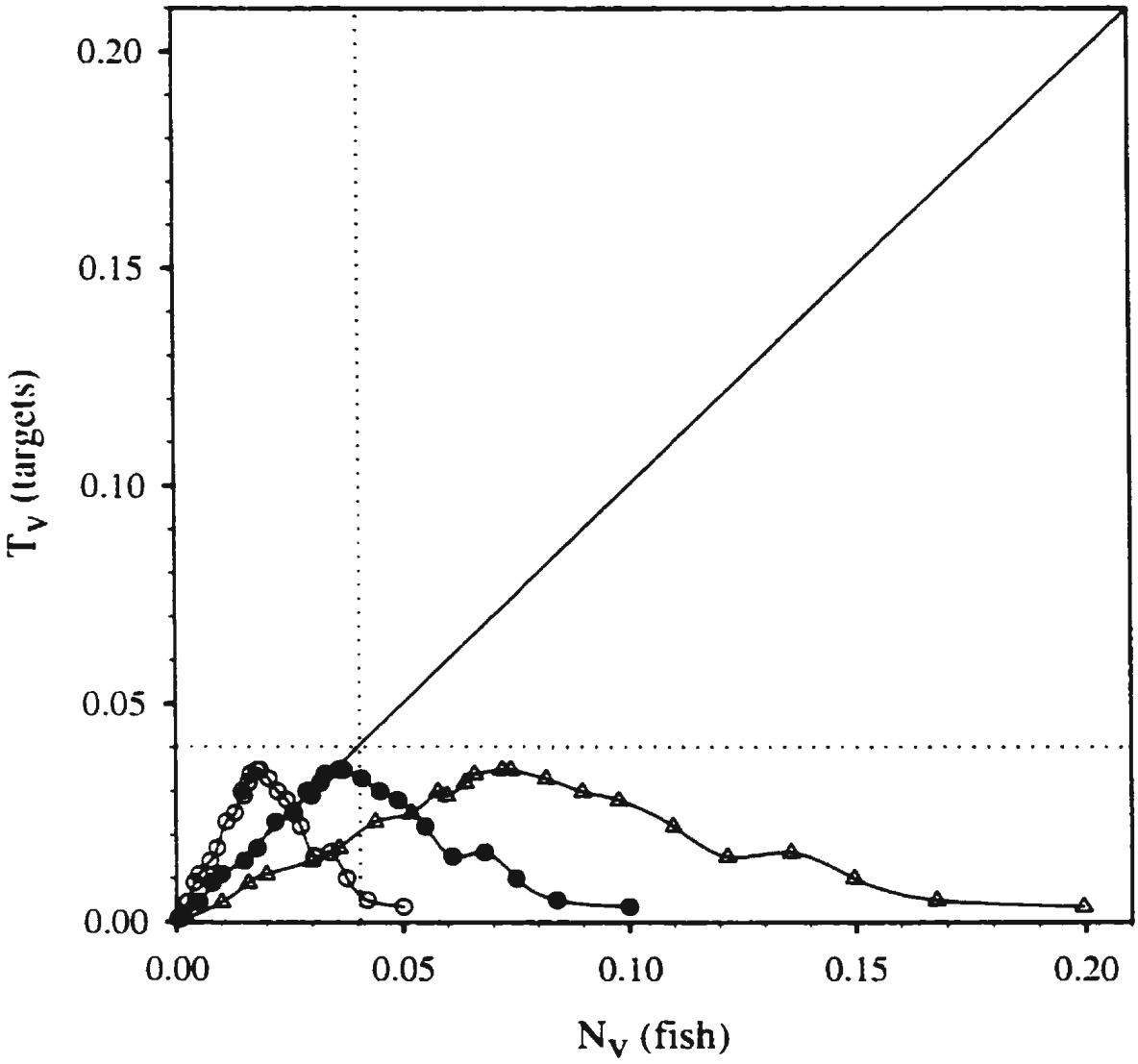


Figure 4.6. Relationship between the number of redfish (N_v) and the number of targets (T_v) relative to one sample volume (solid circles). Open circles and triangles represent values of N_v calculated with a target strength 3 dB lower and higher, respectively, than the correct value. Dotted lines represent N_v threshold values determined empirically.

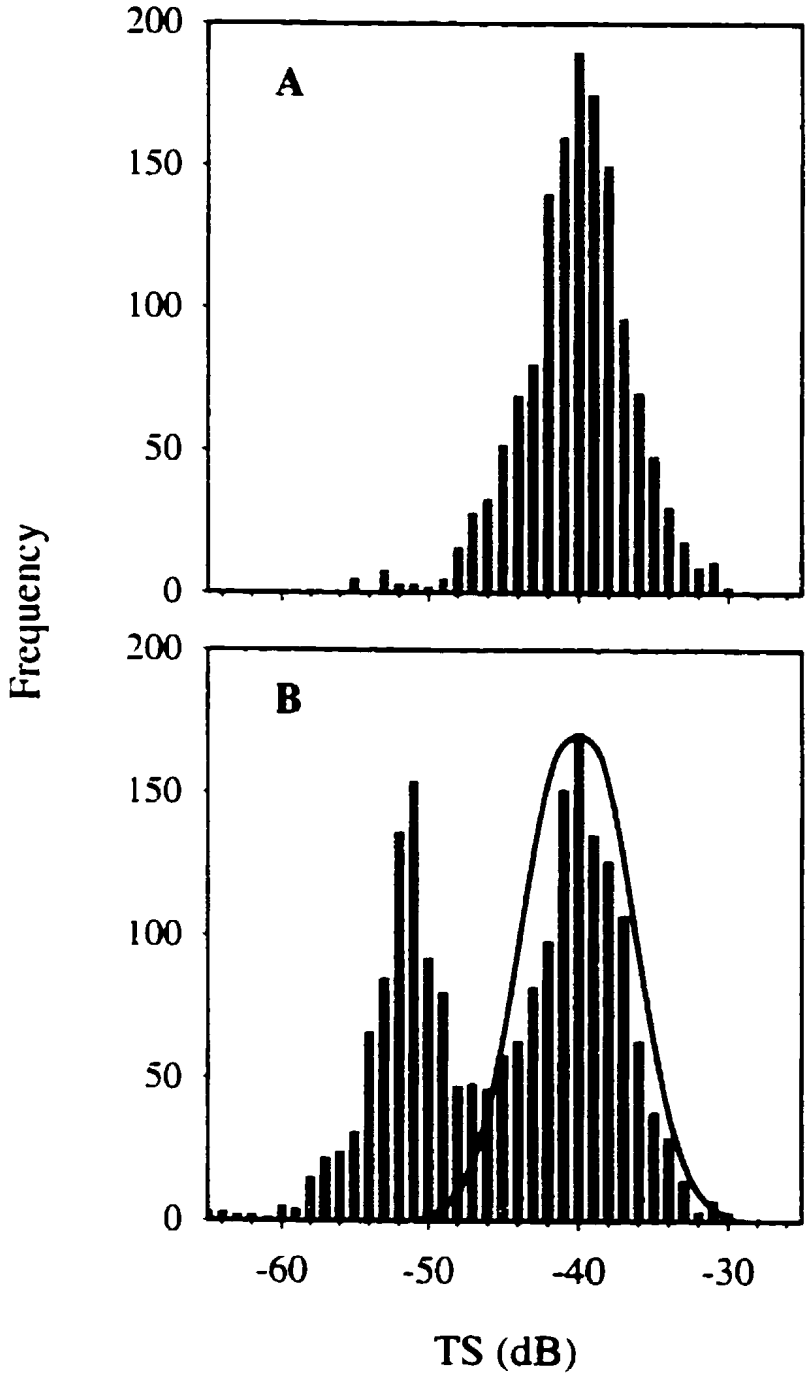


Figure 4.7. Target strength frequency distribution at 38 kHz of a) single traces of redfish and b) a mixed aggregation of redfish and euphausiids (determined by midwater trawling).

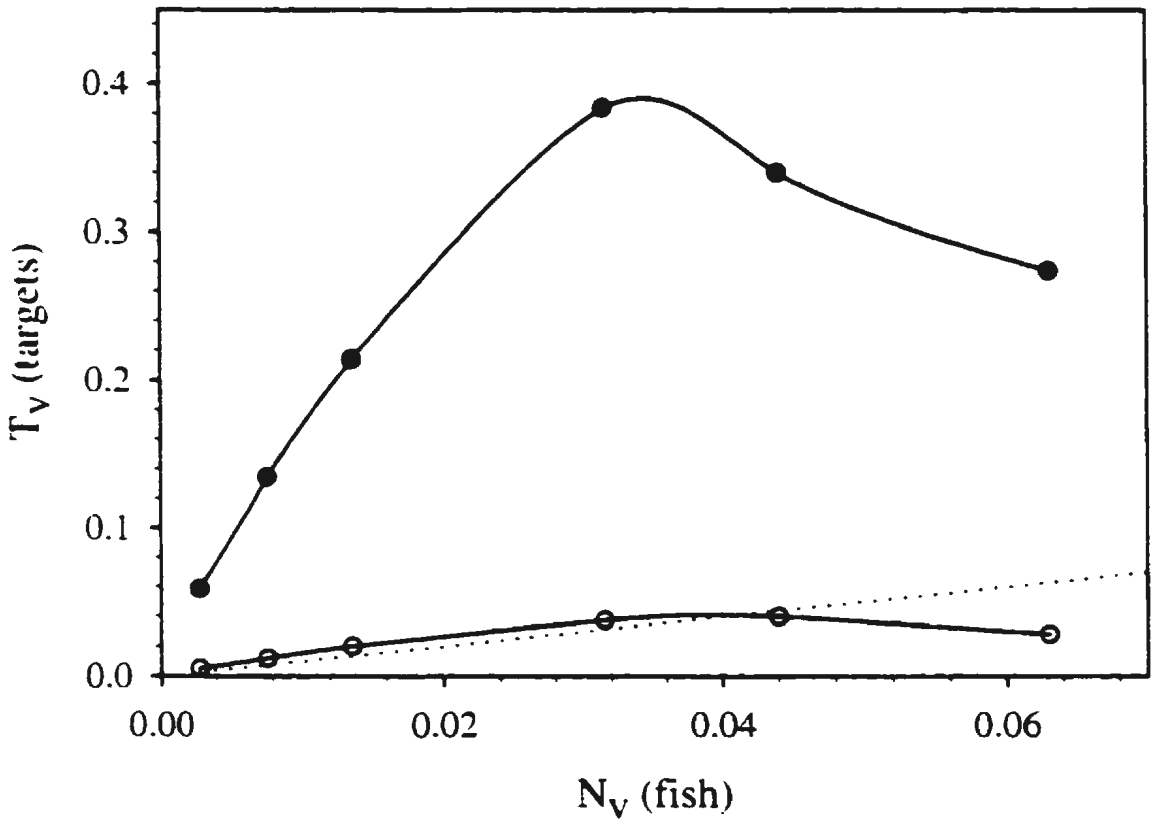
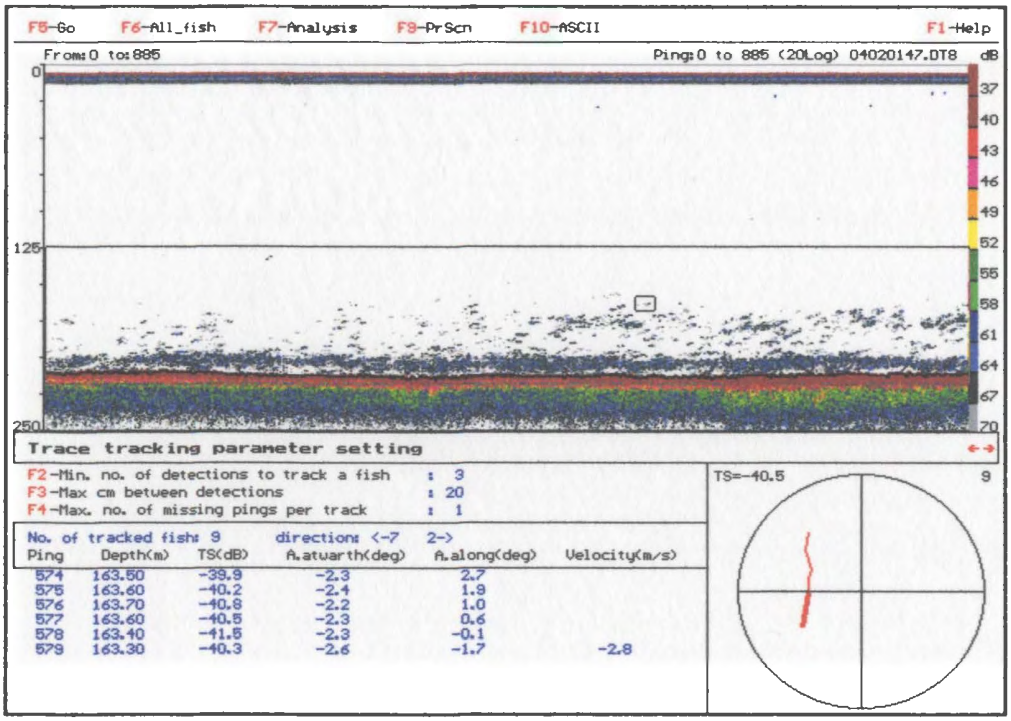


Figure 4.8. Relationship between the number of fish (N_v) and the number of targets (T_v) in 1 sample volume for the mixed aggregation (closed circles) and the filtered redfish signals (open circles). The dotted line represents the expected values (no differences). Smoothing was done through extrapolation.

Chapter 5. *In situ* target strength studies on Atlantic redfish (*Sebastes spp.*)



5.1 Abstract

In situ acoustic target strength (TS) experiments were conducted on Atlantic redfish (*Sebastes* spp.) in Newfoundland waters (1996-1998) using deep-tow dual beam and hull mounted split beam echosounders (38 kHz). Dual and split beam mean TS did not differ. The deep-tow system was deployed at various depths over several aggregations. Calibration corrections were made for depths from 5 – 70 m (< 1 dB). At ranges < 50 m from the top of the fish, TS declined, suggesting avoidance behavior. TS was biased upward at ranges > 200 m and number of fish per sampled volume > 0.04. After controlling for variations related to range, reverberation volume and fish density, TS did not differ with respect to depth, distance from bottom, or fish sex ratio, condition factor or weight. Mean length was the dominant influence on mean TS. Pooled *ex situ* experimental data and controlled *in situ* data (they did not differ), indicated a length based regression (weighted by SE^{-1}) in standard format: TS = 20 log [length (cm)] - 68.7 ($R^2 = 0.49$).

5.2 Résumé

Des expériences *in situ* sur l'indice de réflexion acoustique (IR) ont été conduites sur le sébaste (*Sebastes* spp.) dans les eaux de Terre-Neuve (1996-1998) en utilisant un système à faisceaux doubles sur remorque profonde et un échosondeur de surface à faisceaux partagés (38 kHz). J'ai observé aucune différence entre la moyenne de l'IR mesuré avec le système à faisceaux doubles ou partagés. Le système a remorque profonde a été déployé à différentes profondeurs au dessus de plusieurs agrégations. Une correction pour la calibration a été mesurée de 5 – 70 m (< 1 dB). À une portée de < 50 m au dessus des poissons, l'IR a baissé, suggérant une réaction de fuite. l'IR était biaisé vers le haut à des distances > 200 m et une densité de poissons par volume échantillonné > 0.04. Après avoir controllé pour les variations duent à la portée, le volume de réverbération et la densité de poissons, je n'ai mesuré aucune différence de l'IR en relation avec la profondeur, distance du fond, ou le sexe, poids et l'indice de condition (K) des poissons. La longueur moyenne était le facteur dominant pour expliquer les variations de l'IR. Les données expérimentales *ex situ* associées aux données controllées *in situ* (ces dernières n'étaient pas différentes) indiquent une régression de l'IR basée sur la longueur (pondérée par SE^{-1}) dans le format standard: IR = 20 log [longueur (cm)] - 68.7 ($R^2 = 0.49$).

5.3 Introduction

Accurate target strength (TS) information is an essential element of acoustic surveys of fish populations (Foote, 1987). Methods of TS estimation using dual-beam and split-beam techniques enable direct measurements of fish *in situ* (Ehrenberg, 1983; Foote 1991a), and theoretically provide the best estimation of TS to scale integrator outputs (MacLennan and Simmonds, 1992; Rose, 1992). However, several potential biases limit the use of *in situ* TS. Bias can be attributed to the acoustic measurements themselves, in particular the resolution of single targets (Sawada et al., 1993; Soule et al., 1995), or as a result of transducer motion (Furosawa and Sawada, 1991). The complex nature of fish behavior can lead to variations in tilt angle distribution and TS (Foote, 1980) as a consequence of vertical migration and avoidance of the boat or towed body (Olsen, 1990; Kloser et al., 1997). The physiological state of the fish (Ona, 1990) can also affect TS. Furthermore, interpretation of the species and size composition necessary for unbiased TS estimation depends on representative biological sampling (MacLennan and Menz, 1996). However, all fishing gear are selective (MacLennan, 1992) and it is often difficult to sample fish at the exact time and location at which they were ensonified. The most realistic solution to these problems has been to conduct in situ TS experiments under optimal or well measured conditions (eg. Traynor, 1996; Rose and Porter, 1998)

Atlantic redfish (*Sebastes spp.*) are important commercial species and have been acoustically surveyed in many areas including Newfoundland waters (Atkinson, 1989), the Irmenger Sea (Reynisson and Sigurdson, 1996) and the Flemish Cap Bank (Vaskov et

al., 1998). The three species of redfish: *Sebastes mentella*, *S. fasciatus* and *S. marinus* (Scott and Scott, 1988) are difficult to identify from external features alone. Composite groups of *Sebastes* are typically managed as single stocks. Only very limited work has been conducted on redfish TS. Foote *et al.* (1987), Reynisson (1992), and Gauthier and Rose (1998) reported limited *in situ* estimates, while Gauthier and Rose (in press) recently presented *ex situ* results for TS of redfish kept in sea cages.

In this paper, I describe a series of *in situ* TS experiments on Northwest Atlantic redfish using dual-beam and split-beam methods. Measurements were made under a wide range of conditions and over several years. I address potential biases in TS attributable to acoustic technique (split and dual beam), time of day, range of measurements, density of fish, and avoidance behavior. I also compare TS over seasons and years. My objective is to provide a useful model of redfish TS to scale integrator outputs from acoustic surveys.

5.4 Material and Methods

All measurements were made from the Canadian Coast Guard Ship "Teleost", a 63 m stern trawler equipped for acoustic survey with both hull mounted and deep tow acoustic systems. TS experiments were performed in June 1996 and January 1997 using an EK500 echosounder with a hull mounted 38 kHz transducer (6 m from the surface) and a custom built dual-beam system (also at 38 kHz) with the transducer towed behind the vessel. Further experiments were conducted in March and June 1998 using only the EK500 system.

5.4.1 System configuration

TS measurements were made using standard dual-beam and split-beam techniques (Ehrenberg, 1979; 1983). The custom built dual-beam system used in this study was designed and tested by the hydroacoustic division of the Northwest Atlantic Fisheries Centre (C. Stevens and C. Lang, Department of Fisheries and Oceans, *personal communication*). The deep tow transducer was a 38 kHz EDO SP303LT-38 dual-beam composed of 113 elements distributed in 5 rings with active electronic beamforming. The transducer diameter was 39 cm and the half power angles in degrees for the narrow and wide beam are 7° and 14° respectively. Power was transmitted *via* an Instrument Inc. S14-4 class SS amplifier of 6 kVA and received by a Biosonic Inc. ES2000 with 146 dB dynamic range (at 1 kHz bandwidth). The transducer was installed in a heavy stainless steel towed body (500 kg, Indal Techno Inc.) deployed with a Fathom model 6-935 handling system designed for stern towing from the CCGS Teleost. A multichannel 400 m armored tow cable connected the towed transducer to the transmitter-receiver system. The cable was fitted with hydrodynamic fairings to reduce drag and vibration.

The split beam ES38B transducer (Kongsberg, Simrad) had a beamwidth of 7.1° between half power points. The maximum gain compensation was set to 3 dB to correct for directional attenuation as sound radiates away from the beam axis. In addition, strict positional restrictions were implemented between consecutive echoes. In a split-beam system, different arrival times of acoustic wavefronts to the quadrants causes differences

in the phase angle of the electrical output signal (MacLennan and Simmonds, 1992). The average electrical phase jitter between samples inside an echo pulse (phase deviation between the beam quadrants) was set to 2 phase steps, where 1 phase step is equal to a 2.8125 electrical degree difference in the carrier frequency (64 phase steps = 180 electrical degree). For the dual beam system, signals were filtered to reject pulses narrower than the transmission pulse and wider than 1.2, 1.5, and 1.8 times the pulse width at the half, quarter and eighth pulse heights. Data were also rejected if the ratio of the width at the half to quarter heights and quarter to eighth heights were below 0.75. Only targets < 3 dB of the acoustic axis were included in the analyses. A transmit pulse duration of 0.8 ms and a ping rate of 1 s^{-1} were used for both systems.

5.4.2 Calibration

Standard calibration procedures for scientific echosounders are based on the measurement of a copper or tungsten-carbide sphere having known acoustic properties (Foote and MacLennan, 1984). Temperature and sound speed can influence the echo measurements. Hence, calibrations are best performed under survey conditions (Demer and Hewitt, 1992). The two acoustic systems used in this study were calibrated on site before each *in situ* TS experiment using procedures described by Foote et al. (1987). A calibration with the dual beam transducer at deeper operating depths was performed after the sea research was completed.

Placement of the acoustic transducer well beneath the ocean surface and closer to

the fish can greatly reduce bias in TS measurements attributable to spreading and absorption signal loss (Kloser, 1996). I used the dual beam transducer at depths to 300 m. Although repeatedly calibrated close to the surface (< 10 m), this is the first report of its calibration a depths. I calibrated the system at incremental depths from 4.5 to 72 m to test the effect of ambient pressure (depth) and change in temperature on the sensitivity of the instrument.

Calibrations were performed in Bull Arm, Trinity Bay, Newfoundland in September 1998. The CCGS Teleost was anchored in a sheltered and deep channel (total depth 85 m). An adjustable frame was installed on the towed body to provide three attachment points for a 38 mm tungsten-carbide calibration sphere. The sphere was centered on the beam at a range of 6.2 m from the transducer and a weight was attached at 8 m to minimize swing and drag induced by currents. Calibrations were conducted with the transducer at depths of 4.5, 9.4, 21.9, 32, 42, 51.7, 61.8, and 71.9 m. At each depth station, acoustic pulses of 0.8 ms were transmitted at a rate of 1 ping $\cdot$ s^{-1} for approximately 5 minutes. Stations were occupied during lowering and raising of the system. This procedure was repeated 7 times within 3 days. Following each experiment, a complete depth profile of temperature and salinity was taken using a CTD seabird probe. The TS of the tungsten-carbide sphere was calculated employing standard dual-beam techniques (Traynor and Ehrenberg, 1979) using the parameters obtained in surface calibration (source level of 225.8 dB, narrow and wide beam receiver sensitivity of –186.5 and –185.7 dB, respectively, and a wide beam roll off of 0.66). Means and standard

errors were arithmetically averaged from the backscattering cross section of the target prior to logarithmic transformation (Foote, 1987).

The expected TS of the tungsten-carbide standard target at a particular depth was calculated from a polynomial equation derived from sound speed - TS curve provided by the manufacturer (Equation 1). The equation had the form:

$$(1) \quad TS_i = 9.9424 \cdot 10^{-5} + (4.8692 \cdot 10^{-2} \cdot c_i) - (1.1962 \cdot 10^{-4} \cdot c_i^2) + (4.5551 \cdot 10^{-8} \cdot c_i^3)$$

where TS_i is the target strength of the sphere and c_i is the sound speed in water at depth i. Sound speed was calculated according to MacKenzie (1981) using the depth profiles of temperature and salinity obtained after each experiment.

Echosounders typically implement a range compensation (Time Varied Gain) on all measured targets:

$$(2) \quad TVG = 40\log R + 2\alpha R$$

where R is the range from the transducer in m and α is the absorption coefficient in db $\cdot$ m^{-1}. The custom-built transducer used in this study calculated gain and TVG in a combined form, using fixed sound speed:

(3) $$TVG = G_0 + (40\log + 2\alpha_0)\left(\frac{c_0}{2}t\right)$$

where G_0, c_0, and α_0 are, respectively, gain in dB, sound speed in $m \cdot s^{-1}$, and absorption coefficent in $db \cdot m^{-1}$. The propagation time (t) is the total time (in s) for the acoustic wave to travel from the transducer to the target and back to the transducer. Propagation time depends on the range (R_i) to the target and the average sound speed between the transducer and target (C_{avg}):

(4) $$t_i = \frac{2R_i}{C_{avg}}$$

For the target at fixed range, the difference in average sound speed as the transducer moved deeper introduced a bias in the TVG correction. If we consider the average sound speed between the target and the transducer at the surface as a reference, the bias in dB at any given transducer depth will be proportional to the error expressed in the range reported by the echosounder:

(5) $$Bias_i = 40\log\left(\frac{R_i}{R_{ref}}\right) + 2\alpha_0(R_i - R_{ref})$$

where R_{ref} is the actual distance of the target to the transducer and R_i is the new reported range to the target at transducer depth i. If we approximate α_0 as 0.01 $dB \cdot m^{-1}$ (a typical

value for absorption coefficient at a frequency of 38 kHz in sea water), the equation can be simplified to:

$$\text{Bias}_t = 40\text{Log}\left(\frac{R_t}{R_{ref}}\right) + 0.02(R_t - R_{ref}) \quad (6)$$

5.4.3 In situ *TS measurements*

Large aggregations of redfish were studied on the edge of the Green and Grand Banks of Newfoundland (NAFO Divisions 3Ps – 3O) between depths of 100 to 800 m (Fig. 5.1). In this area, both species of beaked redfish are present (*Sebastes mentella* and *S. fasciatus*), and *S. marinus* is relatively uncommon (Power, 1998). For this study, no species discrimination was made. During each experiment (1996-1998), shoals of redfish were acoustically monitored for a period of at least 24 hours (Table 5.1). At each site, transects of 1.5 to 5 nautical miles were ran at 5 knots at randomly determined positions along and across the Continental slope. Species and size composition were determined using an instrumented Campelen 1800 bottom trawl fished at depths and locations as close as possible to the acoustic transect using GPS (Global Positioning System) information. For transects across the continental slope, fishing sets were performed at depth intervals of approximately 100 m. Only sites where 90% or more of the catch (by weight) was redfish were used for TS analysis. A subsample of 200 to 500 fish was used to measure individual length, weight, and gender. Condition factors were calculated as:

$$K = 100wl^{-3} \quad (7)$$

with whole wet weight (w) measured in grams and length (l) in cm. Diamond IX or IGYPT midwater trawls were used to identify pelagic traces when necessary. In 1996 and 1997, the deep-tow dual beam system was deployed in multiple passes over the same transects at increments of 20 to 50 m from the surface to 300 m depth. The dual beam system was used simultaneously with the EK500 system (pulse synchronized).

To determine mean TS, backscattering cross sections were arithmetically averaged prior to logarithmic transformation (Foote, 1987). TS-length regression models were generated as TS (dB) = a log [length (cm)] + b and TS (dB) = 20 log [length (cm)] + b (Love, 1977). The number of fish relative to 1 effective reverberation volume was calculated according to Sawada et al. (1993) as:

(8) $$N_v = \frac{c\tau\psi R^2 n_{EI}}{2}$$

where c is the speed of sound in water in $m \cdot s^{-1}$, τ is the transmit pulse duration in s, ψ is the equivalent beam angle in steradians, R is the target range in m and n is the volumetric fish density in fish $\cdot$ m^{-3}. The volumetric fish density was calculated for bins of 10 m depth by 300 to 500 pings (800-1400 m) using volume scattering coefficients (s_V) and TS estimated from catch data and previous TS-length models for redfish (Gauthier and Rose, 1998).

At sea, several additional variables that could influence TS were measured. These included time of day, distance of fish from the transducer (avoidance behavior and threshold effect), density of fish (N_v), and distance of fish above the bottom (buoyancy effect). Stepwise regression and a general linear modelling approach were used in an attempt to explain variations in TS according to fish characteristics (mean length, mean weight, condition factor K and sex ratio), estimation method (split vs dual beam), time of year (mission date), and depth of the fish aggregation.

5.5 Results

5.5.1 Calibration

Representative depth profiles of sound speed, expected TS of the tungsten-carbide sphere, and TVG correction factor for the calibration experiments on the deep tow system are shown in Fig. 5.3. Profiles from the 7 experiments were relatively similar in trend, although absolute values differed because tides affected temperature and salinity. At 4.5 m from the surface, water temperature varied from 5.4 to 12.2 °C throughout the experiment (3 days). Temperature change did not affect the dual beam transducer sensitivity (calibration error within 0.1 dB).

The observed TS of the tungsten carbide sphere (TS_o) decreased significantly ($p < 0.001$, $r^2 = 0.92$) with depth due to transducer hysteresis (Fig. 5.4). The depth corrected TS (TS_c) was:

(9) $$TS_c = TS_o + 0.003\,(D_T - 4.5)$$

where D_T is the absolute transducer depth in m. An offset of 4.5 m represents the reference depth for calibration. The pressure correction factor was independent of the correction for sound speed. This correction factor was extrapolated for the entire deployment range of the transducer. At the maximum range used in this study (~300 m) the correction was less than 1 dB.

5.5.2 In situ TS measurements

Redfish exhibited diel patterns of schooling behavior in all surveys. During the day, fish were distributed in aggregations close to the bottom, packing densities were high and single targets were seldom recorded. At dusk, redfish migrated into the water column and individuals became more widely dispersed. Fish returned to the bottom at dawn or shortly thereafter. The number of targets recorded per hour sharply increased at dusk and decreased at dawn (Fig. 5.5). Few targets were recorded during the day (< 50).

To simultaneously test the effects of transducer depth and range to the fish, the mean TS of three large aggregations of redfish was measured with the transducer at various depths using the deep-tow dual beam system (Fig. 5.6). In each case, the TS of redfish decreased as the transducer depth increased. However, the density of fish was often high at shallow transducer depths, as a result of the larger reverberation volumes at

the depths of the fish (double circles in Fig. 5.6). For measurements made at similar horizontal scales, Sawada et al. (1993) showed that significant bias in fish TS occurred at N_v values above 0.04. To assess such an effect of density on the TS of redfish, the TS in each aggregation was standardized by subtracting the mean estimated at $N_v < 0.04$ (Fig. 5.7). TS was biased upward above a density threshold of 0.04 fish.

The TS of redfish was measured at various ranges from the transducer (in layers of 10 m) at different locations and depths within each aggregation where $N_v \leq 0.04$ (diagram of Fig. 5.8). At ranges < 50 m from the transducer, mean TS was lower by 2-4 dB than at range from 50 – 200 m. At ranges between 50 and 200 m, TS did not differ. At ranges > 200 m, TS increased to levels greater than at 50 – 200 m (Fig. 5.8). TS did not differ with respect to distance of the fish from the bottom at ranges between 50 and 200 m (Fig. 5.9A). However, when the transducer was closer than 50 m from the top of the redfish aggregation, the entire column showed a decrease in TS (Fig. 5.9B).

Eight redfish aggregations were measured simultaneously with dual and split beam echosounders (Fig. 5.10). TS measurements with the dual beam were limited to ranges between 50 - 200 m from the transducer. A threshold of 0.04 N_v was applied to all data. Univariate analysis of variance indicated that there was no significant difference between the mean TS obtained with the two methods ($p > 0.1$; DF = 1,16; F = 0.33). The number of accepted targets was generally lower for the split-beam system, since measurements were made at much greater transducer range and reverberation volume. TS

frequency distributions from split beam were in many cases narrower than from dual beam (up to 8 dB difference in spread). However, at half peak height, the width of the histograms for the split-beam method was, on average, higher than for the dual- beam method.

The results of the *in situ* redfish experiments are summarized in Table 1. For each site, redfish comprise > 90% of the catch (by weight) and length distributions were monotonic. The mean number of fish per volume (N_v) was below 0.04 in all but 3 cases (bold values in Table 5.1). Those 3 cases represented small groups of fish, in which sampling intervals were 200-300 pings less than at other sites (Chapter 4). A general linear model approach and stepwise selection of variables were used to identify factors that influenced TS. Length and weight were logarithmically transformed prior to computations. Of all factors considered, only length of redfish sampled and mission date (time of year) had a significant effect on TS (Table 5.2). The interaction term (length x date) was also significant indicating that the slope of the regression between TS and length differed among dates.

For all *in situ* experiments (n = 31), mean fish length ranged from 14.8 to 32.3 cm and TS ranged from –44.3 to –38.2 dB (Fig. 5.11). The best fit regression of TS on length was TS (dB) = 16.8 log [length (cm)] – 64.2 (95% CI –64.4 to –63.9; $R^2 = 0.69$) and in the standard form TS (dB) = 20 log [length (cm)] – 68.5 (95% CI -68.8 to -67.2; $R^2 = 0.67$). *Ex situ* data from encaged redfish are also plotted in Fig. 5.10 (Gauthier and Rose,

in press). A TS – length model based on the *ex situ* data does not differ either in slope (when not forced to 20) or intercept from the *in situ* model. A model based on a pooling of all *in situ* and *ex situ* experiments indicates TS = 20 log[length (cm)] – 68.3 (R^2 = 0.70, 95% CI –68.6 to –68).

In a attempt to account for differing precision in the various data (Table 1), a weighed regression was calculated using the inverse of the standard error of the mean backscattering cross-section as a weighing factor (SE^{-1}). The resulting model had the form TS (dB) = 17.1 log [length (cm)] – 64.9 (95% CI –65.1 to –64.6; R^2 = 0.52) and in the standard form TS (dB) = 20 log [length (cm)] – 68.7 (95% CI –69.0 to –68.4; R^2 = 0.50). A weighted model (with SE^{-1}) based on a pooling of all *in situ* and *ex situ* experiments (Table 1 and 3) indicates TS (dB) = 17.5 log [length (cm)] – 65.2 (95% CI – 65.5 to –64.9; R^2 = 0.49) and in the standard form TS (dB) = 20 log [length (cm)] – 68.7 (95% CI -69 to –68.3; R^2 = 0.48). The unpooled, pooled, unweighted and weighted standard regression intercepts did not differ (P's < 0.05).

5.6 Discussion

Calibration of acoustic instruments is essential to precision and reliability of TS measurements (Foote et al., 1987). For the deep-tow dual beam system, calibration presented several challenges. To measure the tungsten-carbide sphere with the transducer at different depths, I had to position the sphere at a distance that represented a trade-off between stability (on-axis position) and range from the transducer. Because of potential

change in the relative sensitivity of the narrow to wide beam, the sphere had to be as steady as possible on the axis of the beams. At a distance of 6.2 m, the sphere was stable and located just outside the near-field of the transducer. The experiment was repeated under different environmental conditions over several tidal cycles (with different current velocities and directions) to ensure that observed differences were not caused by movement of the sphere. The results obtained in this study are of the same order as observed by Kloser (1996) in the calibration of a EDO Western 38 Khz split-beam echosounder mounted on a deep-towed body. Kloser (1996) noted that the TS of a 60 mm copper sphere measured at 1000 m depth was almost 3 dB lower than at 100 m. If extrapolated to a depth of 1000 m (well beyond the maximum range of the system used for this study) the correction factor I determined would be of approximately 3 dB.

No reliable measurements of *in situ* TS of redfish were possible during daylight hours as a consequence of the demersal behavior and dense shoaling activity of these species. Hence, time of day had a strong influence on TS measurements. My observation of vertical migration in redfish was consistent with previous studies (Beamish, 1966; Atkinson, 1989). Diel vertical migration in redfish may have a significant impact on the catchability and efficiency of fishing gear (Michalsen et al., 1996; Casey and Myers, 1998), which in turn could bias measurements of fish size distribution.

In this study, high signal to noise ratio conditions were predominantly encountered. Sumbeam signal thresholding was therefore set at low levels with little

effect on TS distribution of fish, except at far ranges where spreading and attenuation losses were important. Beam angle thresholding was kept narrow throughout the experiments (within -3 dB) to ensure accurate TS estimates and to minimize errors due to multiple scattering. Other factors influenced TS, including the presence of other species (multiple targets of euphausiids) and the density of the fish (Sawada et al., 1993). These factors depend in part on the reverberation volume and are thus affected by the range of observation. Sound absorption and beam thresholding are also range dependent (Weimer and Ehrenberg, 1975; Foote, 1991b). For redfish measured with the deep tow dual beam system, a significant bias towards smaller targets was observed at ranges above ~200 m (thus the advantage of using a deep-tow system). Measurements of the same aggregation of fish made at ranges up to 350 m with the hull-mounted split beam transducer were comparable to the dual-beam measurements made within 200 m range, suggesting that the split beam system was more robust at greater ranges. Backscattering cross sections measured with split beam were slightly less variable than those obtained with dual beam (means were not significantly different). Previous studies indicated that bias and errors in TS associated with beam patterns are more important in dual beam systems, and that this technique is more sensitive to the presence of noise (Ehrenberg, 1979; 1983; Traynor and Ehrenberg, 1990; Ehrenberg and Torkelson, 1996). However, the dual beam system was mounted in a deep towed body that enabled measurements at close range to the fish. Use of this system allowed a decrease in the acoustic range to the ocean floor, which greatly reduced the acoustic dead (or shadow) zone (Kloser, 1996; Ona and Mitson, 1996), thus enabling the measurement of targets closer to the bottom.

The data indicated a significant change in TS when the deep-towed body approach to within 50 m range from the redfish aggregation. Several studies (Olsen, 1979; 1981; Halldorsson, 1983; Olsen et al., 1983) have suggested that reductions in acoustic backscattering can occur if fish adopt a downward swimming position while avoiding a vessel. Barange and Hampton (1994) showed that during trawling the TS of Horse mackerel (*Trachurus trachurus capensis*) was up to 12 dB lower than prior to and after trawling. The declines of approximately 3 dB observed in TS when the towed body was at ranges of < 50 m from redfish are consistent with a significant change in aspect to a downward orientation, because directivity is relatively weak in these species (Gauthier and Rose, in press). Such behavior was observed at ocean depths of 200 to 500 m during the night, which suggests that fish were reacting to noise and/or pressure waves (eg. Cable strum) rather than visual stimuli. Fish lower in the aggregation may have reacted by following or "imitating" their closest neighbors. Kloser and al. (1997) observed that Orange roughy (*Hyplostethus atlanticus*) in deep water (> 700 m) responded by moving away and schooling tightly when the towed transducer was less than 150 m from the aggregation.

Fish length was the sole fish characteristic that explained a significant amount of the variation in TS. However, there was a difference attributable to sampling dates. Sampling effort and size distribution of fish differed among dates, making interpretation of this result somewhat problematic. Nevertheless, it is possible that seasonal trends in TS exist as a consequence of unmeasured physiological differences. For example, Ona

(1990) showed that stomach fullness and gonad maturation can significantly alter TS. Furthermore, seasonal change in feeding and swimming behavior could also explain the discrepancy, as these factors could lead to significant change in orientation distribution (Foote 1980). I also considered the possibility that weather may have influenced the results. However, for all data presented, sea conditions were relatively fair throughout (winds < 20 knots) and it is unlikely that observed differences are due to ship motion or sea turbulence.

The TS-length regression model proposed is in fair agreement with published data on physoclists (MacLennan and Simmonds, 1992). There have been few measures on *Sebastes sp*. The data from this study indicate an intercept of –68.7 (weighted standard 20logL form) that is approximately 1.5 dB lower than reported in previous studies, i.e. -67.1 for *in situ* measurement of redfish in the Norwegian sea (Foote et al., 1986) and –67.5 for a general model on physoclists proposed by Foote (1997). Reynisson (1992) reported average TS of –40 dB for redfish of 32.9 cm mean length measured with split-beam system (equivalent to a 20log intercept of -71.3). Using a single beam technique, Orlowsky (1987) obtained an intercept of –69.4 for redfish of similar size to those measured by Reynisson (1992). My TS model on encaged redfish collected in coastal Newfoundland waters indicated an intercept of –68.1, a difference of only 0.6 dB from the *in situ* data (Gauthier and Rose, in press). When pooled together and weighted by the SE^{-1} of the mean backscattering cross-section of each data point, *in situ* and *ex situ* data indicated an intercept of –68.7 (identical to the weighted model for *in situ* data alone).

The consistency of TS data between *ex situ* and *in situ* experiments is encouraging, and I believe this TS model can be useful in the acoustic assessment of redfish in the North Atlantic, and is likely to have applicability in the Pacific Ocean where the diversity of *Sebastes* is much greater.

5.7 Acknowledgements

I thank C. Lang for assistance at sea and reviewing an earlier draft of this paper. I also thank the crew of the CCGS Teleost, R. Forward, W. Hiscock and G.L. Lawson for assistance at sea, and C. Stevens for helpful comments. Funding was received from the Canada Department of Fisheries and Oceans (Redfish Multidisciplinary Research Program) and the Natural Sciences and Engineering Research Council of Canada Industrial Chair in Fisheries Conservation at Memorial University of Newfoundland

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5.9 Tables

Table 5.1. Summary of *in situ* TS (dB) experiments on redfish. Mean backscattering cross-sections ($\hat{\sigma}_{bs}$ in m^2) are shown with standard error (SE). N is the number of accepted targets. K is the condition factor ($100wl^{-3}$). Length, weight, gender and K were individually measured from a subsample of 200-500 fish at each site. Sex ratio represents males to females. Depth is the average depth of targets in the water column. N_v is the mean number of fish in a sample volume.

Date	$\lvert\hat{\sigma}_{bs}$ (SE)$\rvert \cdot 10^{-5}$	TS (dB)	N	L (cm)	W (g)	K	Sex ratio	Depth (m)	N_v	Method
Jul-96	5.50 (0.16)	-42.6	525	21	139	1.55	1.11	169	0.016	Split
	6.92 (0.27)	-41.6	327	23	155	1.48	0.80	198	**0.062**	Split
	6.03 (0.12)	-42.2	1106	22	143	1.38	0.79	218	0.015	Split
	6.61 (0.17)	-41.8	1023	22	143	1.38	0.79	267	0.012	Dual
	7.24 (0.21)	-41.4	602	23	160	1.32	1.12	239	0.025	Split
	8.71 (0.22)	-40.6	1508	23	160	1.32	1.12	319	0.020	Dual
	5.01 (0.10)	-43.0	1949	21.2	139	1.42	0.97	216	0.020	Split
	4.79 (0.08)	-43.2	3697	21.2	139	1.42	0.97	246	0.015	Dual
	5.75 (0.14)	-42.4	1015	21.8	142	1.44	0.53	239	0.023	Split
	7.59 (0.27)	-41.2	1432	21.8	142	1.44	0.88	288	0.018	Dual
Jan-97	7.59 (0.16)	-41.2	1051	21.8	141	1.35	0.07	241	0.013	Split
	6.61 (0.12)	-41.8	2057	22.5	157	1.32	0.46	224	0.012	Split
	7.76 (0.20)	-41.1	3318	22.5	157	1.32	0.46	253	0.007	Dual
	7.76 (0.16)	-41.1	2200	22.5	157	1.32	0.46	284	0.017	Dual

Table 5.1. *Continued*

Date	$\lvert\bar{\sigma}$ (SE)$\rvert \cdot 10^{-5}$	TS (dB)	N	L (cm)	W (g)	K	Sex ratio	Depth (m)	N_v	Method
Jan-97	8.13 (0.33)	-40.9	516	21	127	1.29	0.80	165	0.002	Split
	7.76 (0.36)	-41.1	1043	21	127	1.29	0.80	167	0.003	Dual
	7.24 (0.26)	-41.4	686	21	127	1.29	0.80	209	0.021	Split
	7.76 (0.26)	-41.1	1460	21	127	1.29	0.80	210	0.007	Dual
	13.80 (0.81)	-38.6	131	32.3	463	1.35	1.21	338	**0.071**	Split
	13.18 (0.42)	-38.8	833	32.3	463	1.35	1.21	387	0.025	Dual
	15.14 (0.39)	-38.2	556	28.8	362	1.46	0.31	320	**0.078**	Split
Mar-98	5.25 (0.14)	-42.8	648	22.2	153	1.32	0.47	146	0.009	Split
	5.89 (0.45)	-42.3	128	16.9	73	1.35	-	152	0.024	Split
	6.76 (0.35)	-41.7	132	20.8	125	1.24	0.43	179	0.035	Split
	5.89 (0.20)	-42.3	330	23.6	168	1.25	0.65	196	0.020	Split
	6.61 (0.42)	-41.8	151	23.5	175	1.31	0.72	234	0.022	Split
	3.72 (0.49)	-44.3	170	14.8	74	1.83	-	143	0.019	Split
	5.62 (0.19)	-42.5	357	18.4	94	1.20	-	151	0.023	Split
	6.31 (0.22)	-42.0	339	22.4	153	1.31	0.48	169	0.012	Split
Jun-98	6.17 (0.28)	-42.1	393	22	-	-	-	134	0.023	Split
	12.88 (0.55)	-38.9	404	29	-	-	-	256	0.029	Split

Table 5.2. Statistics of univariate analysis of variance to account for effect on TS (dB).

Source	Sum of squares	DF	Mean square	F	P
Mission date	4.241	3	1.414	4.7	< 0.05
Log (length)	13.495	1	13.495	44.9	< 0.001
Interaction term	4.414	3	1.471	4.9	< 0.01

Table 5.3. Summary of *ex situ* TS (dB) experiments on individual redfish (Gauthier and Rose, in press). Mean backscattering cross-sections ($\hat{\sigma}_{bs}$ in m^2) are shown with standard error (SE). N is the number of accepted pings.

Length (cm)	$[\hat{\sigma}_{bs}$ (SE)] · 10^{-5}	TS (dB)	N
24.5	9.23 (0.16)	-40.35	1477
24.5	8.30 (0.11)	-40.81	1334
25	10.14 (0.03)	-39.94	5559
26.5	11.25 (0.17)	-39.49	1922
26.5	12.88 (0.17)	-38.9	708
27.5	7.64 (0.12)	-41.17	1362
27.5	12.59 (0.13)	-39	1950
27.5	15.03 (0.82)	-38.23	171
28	14.52 (0.13)	-38.38	486
28.5	17.70 (0.51)	-37.52	272
28.5	9.42 (0.15)	-40.26	670
28.5	15.21 (0.06)	-38.18	18533
28.5	13.03 (0.39)	-38.85	262
29	7.21 (0.03)	-41.42	17140
29.5	12.08 (0.17)	-39.18	2993
30	17.10 (0.19)	-37.67	2429

5.10 Figures

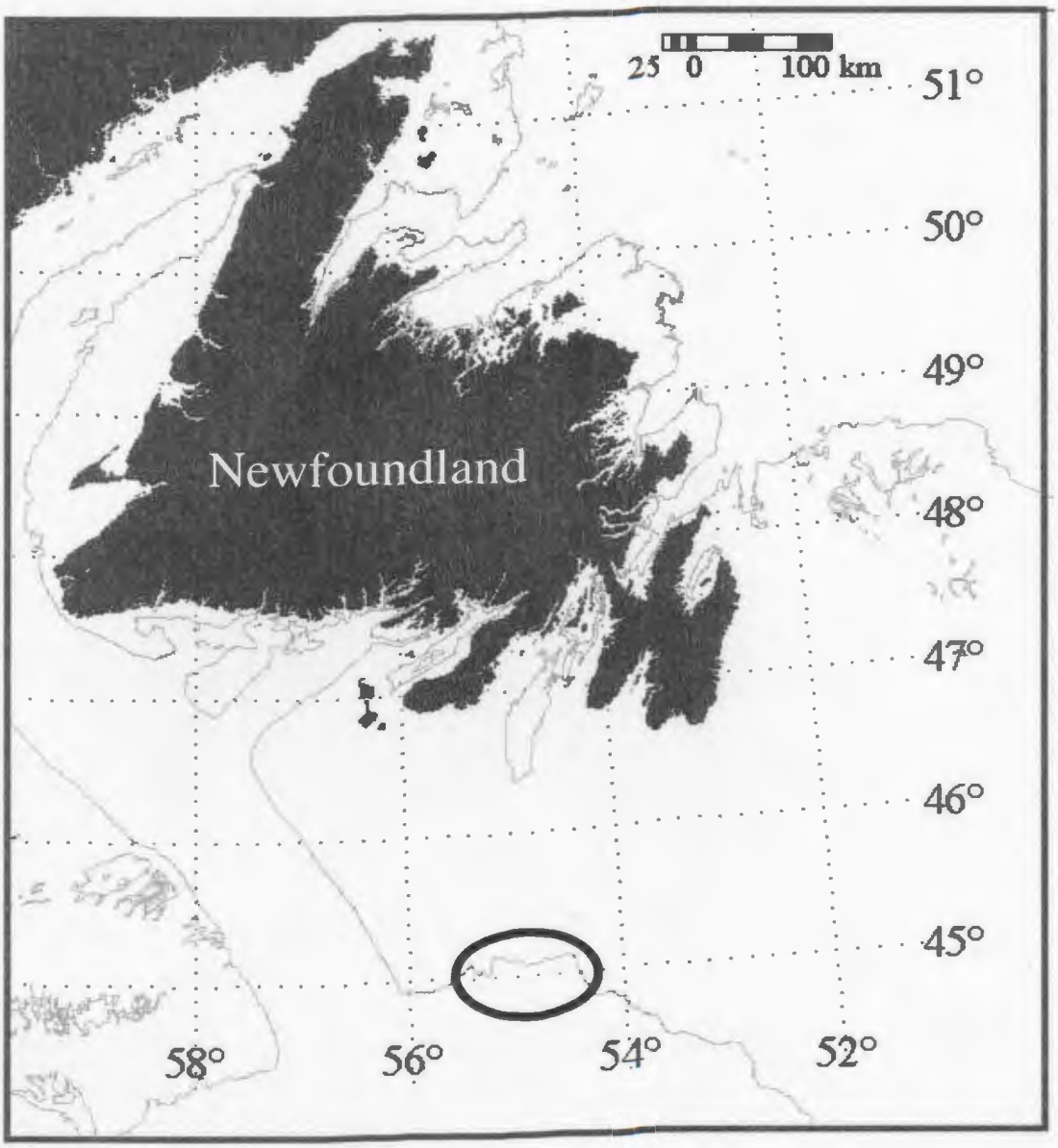


Figure 5.1.Map of Newfoundland with the 200 m depth contour (in grey). The outlined area indicates the location of our *in situ* experiments.

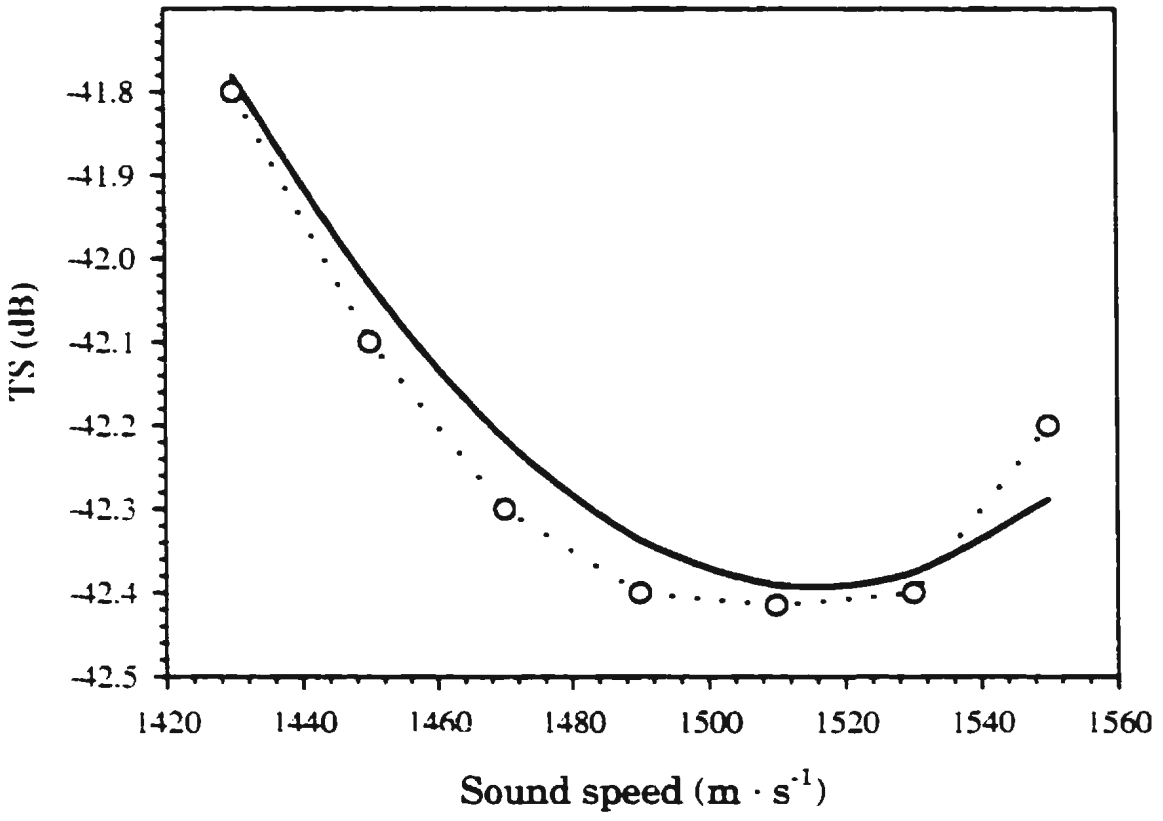
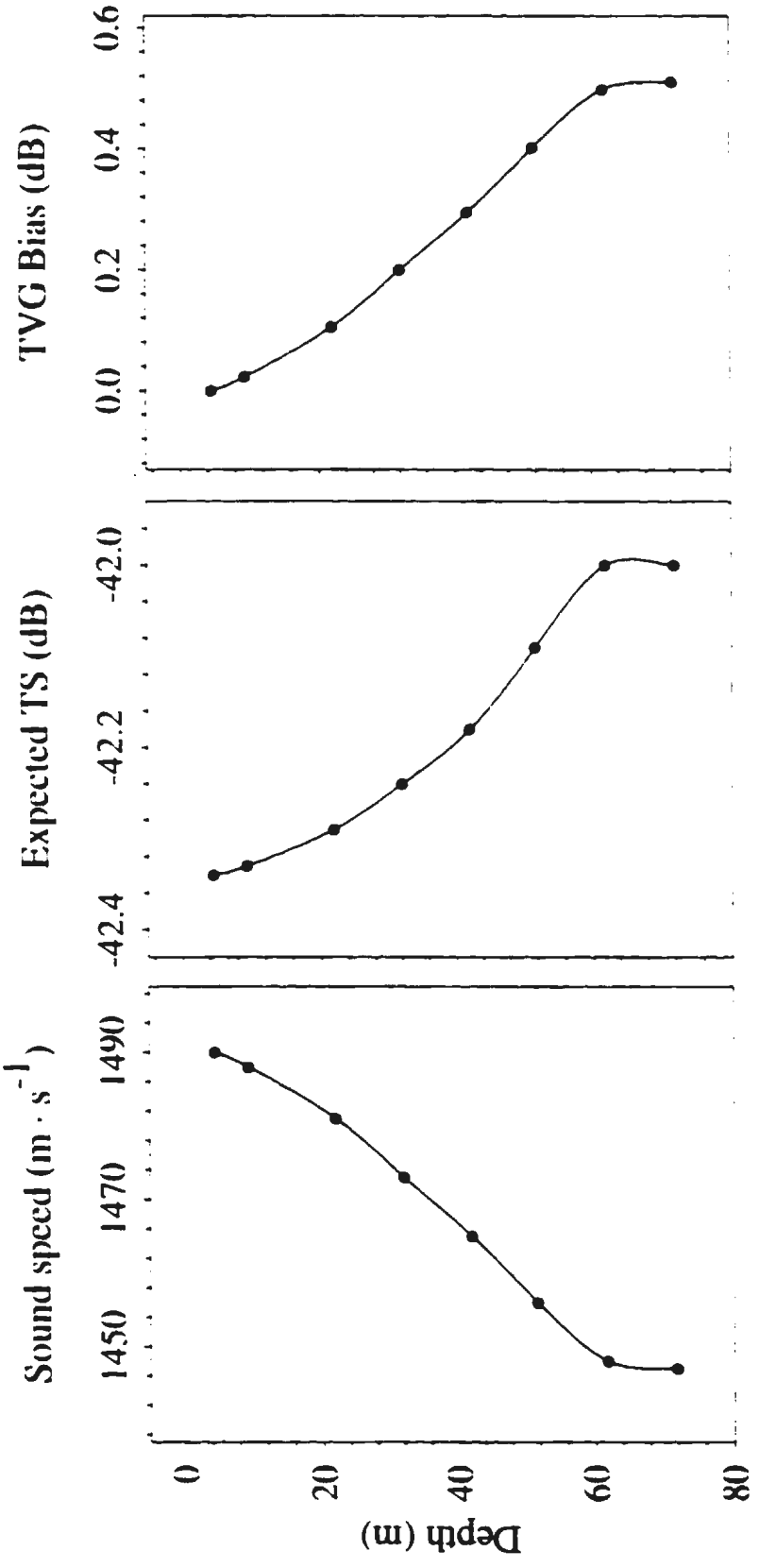


Figure 5.2. Target strength (dB) of the 38.1 mm tungsten-carbide calibration sphere as a function of sound speed in water. The unbroken line represents values calculated using equation (1) and the circles with the doted line represent values given by MacLennan and Simmonds (1992).

Fig. 5.3. Depth profiles of sound speed, expected TS and TVG bias correction for a representative calibration cast with the 38.1 mm tungsten carbide standard target.


Depth (m)
0
20
40
60
80
Sound speed (m · s⁻¹)
1450
1470
1490
Expected TS (dB)
-42.4
-42.2
-42.0
TVG Bias (dB)
0.0
0.2
0.4
0.6

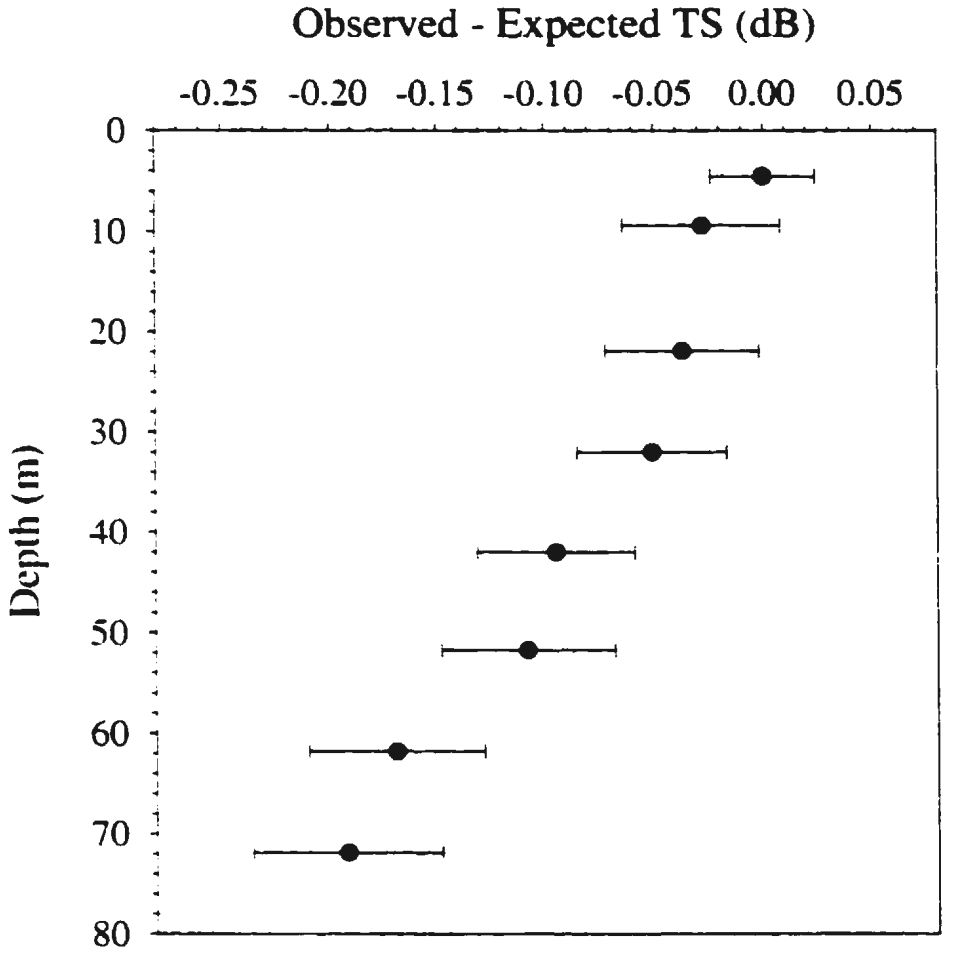


Figure 5.4. Effect of depth on the tungsten carbide sphere TS (dB). Horizontal bars represents ± 1 standard deviation.

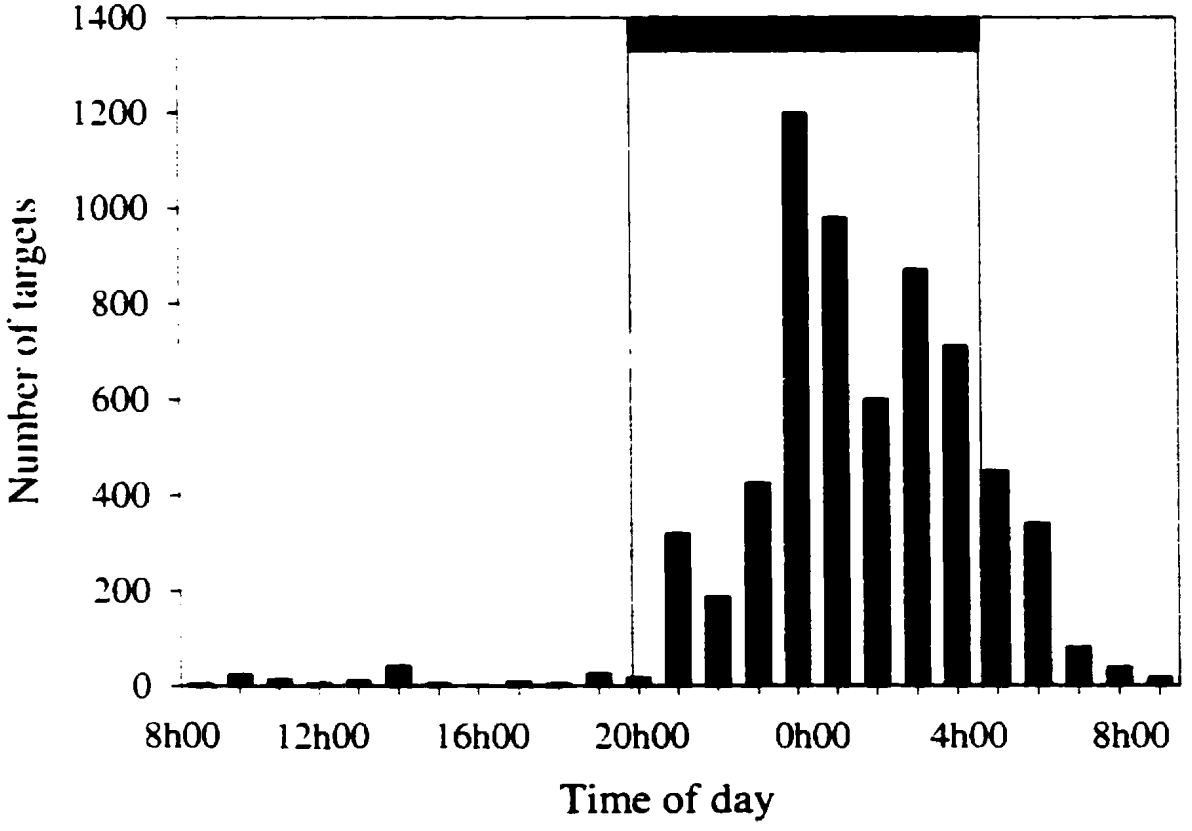
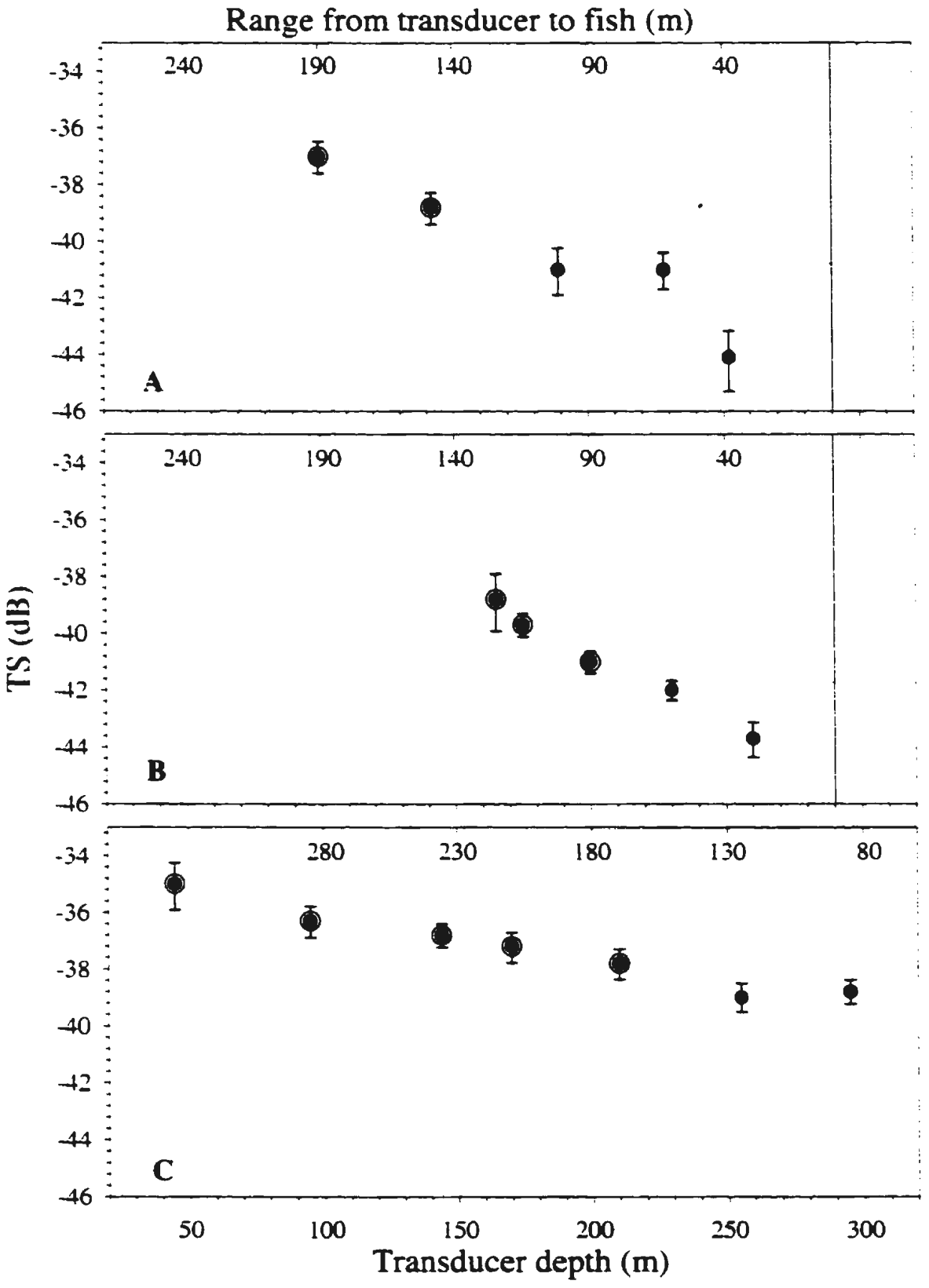


Figure 5.5. Number of targets recorded per hour for a transect line monitored for 24 hours. The black horizontal bar delimites sunset and sunrise.

Figure 5.6. TS in dB (± 2 SE) of three aggregations of redfish measured with the transducer at several depths. Double circles indicate that mean fish densities per sample volume (N_v) exceeded 0.04. The horizontal dashed line represents the TS predicted by the model TS = [20logL (cm)] – 68.1 (Gauthier and Rose, in press).


Range from transducer to fish (m)
240
190
140
90
40
-34
-36
-38
-40
-42
-44
-46
A
B
C
TS (dB)
280
230
180
130
80
50
100
150
200
250
300
Transducer depth (m)

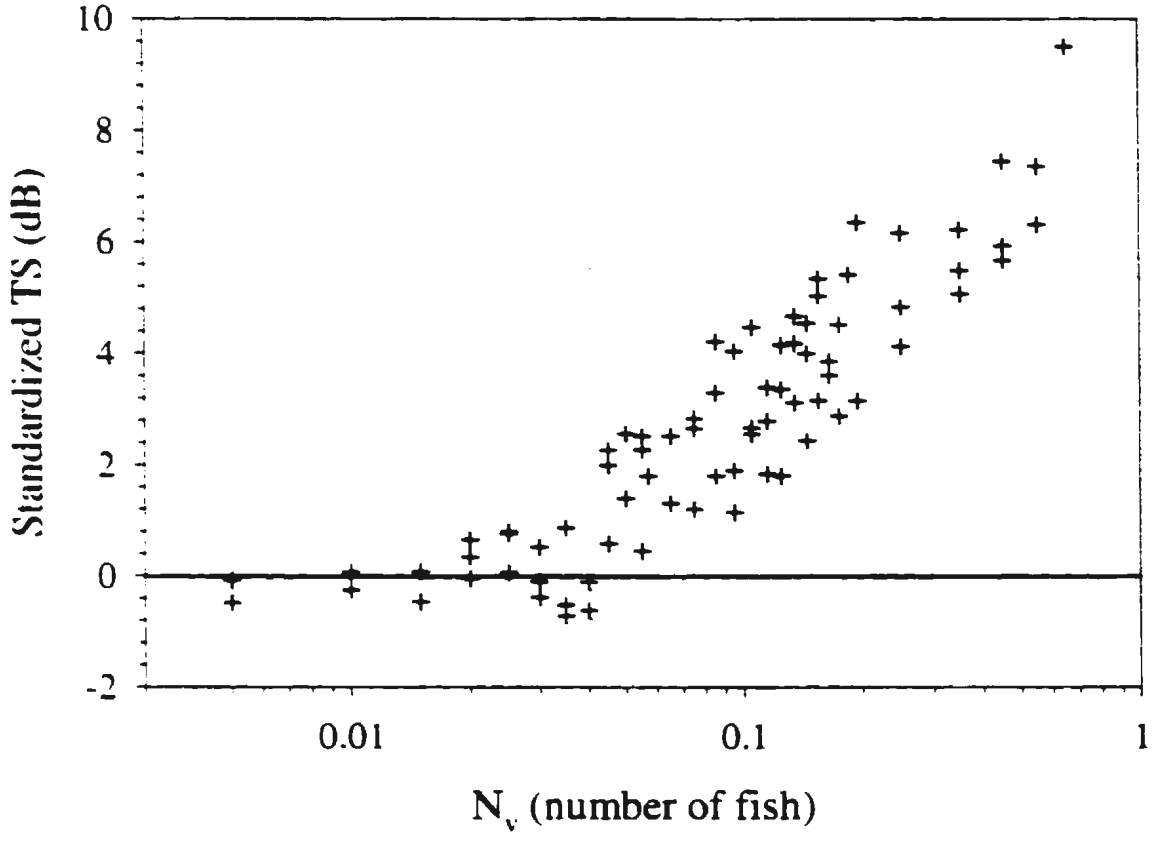


Figure 5.7. Relationship between standardized TS (dB) and the number of fish in a sample volume (N_v). Standardized TS was measured by substracting the mean TS at which N_v was lower than 0.04 fish.

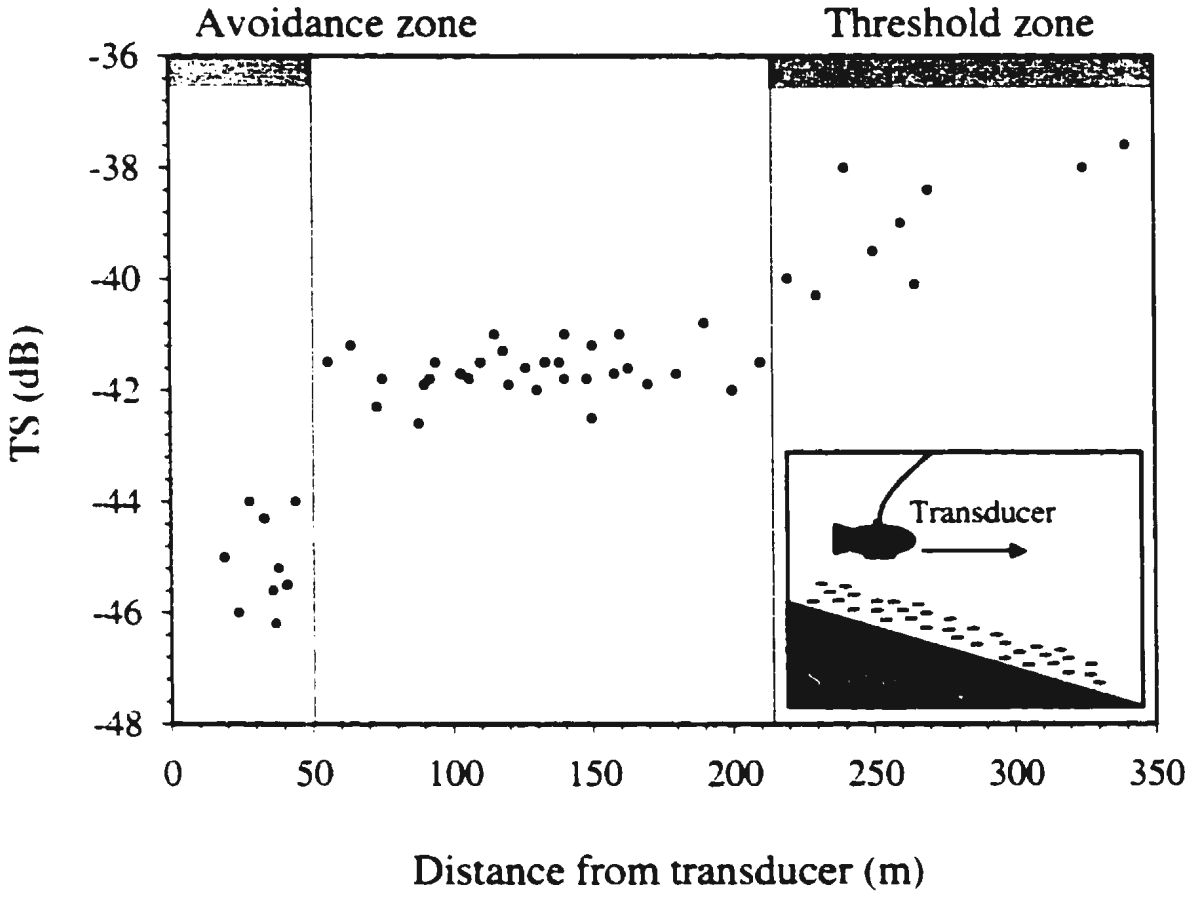


Figure 5.8. TS (dB) of redfish measured at different ranges from the transducer within the same large aggregation. Each point represents the mean of 100 to 500 targets at densities < 0.04. The inset diagram illustrates the sampling strategy. The grey zone on the left indicates a potential avoidance reaction, while the grey zone on the right indicates the range at which threshold biases become significant.

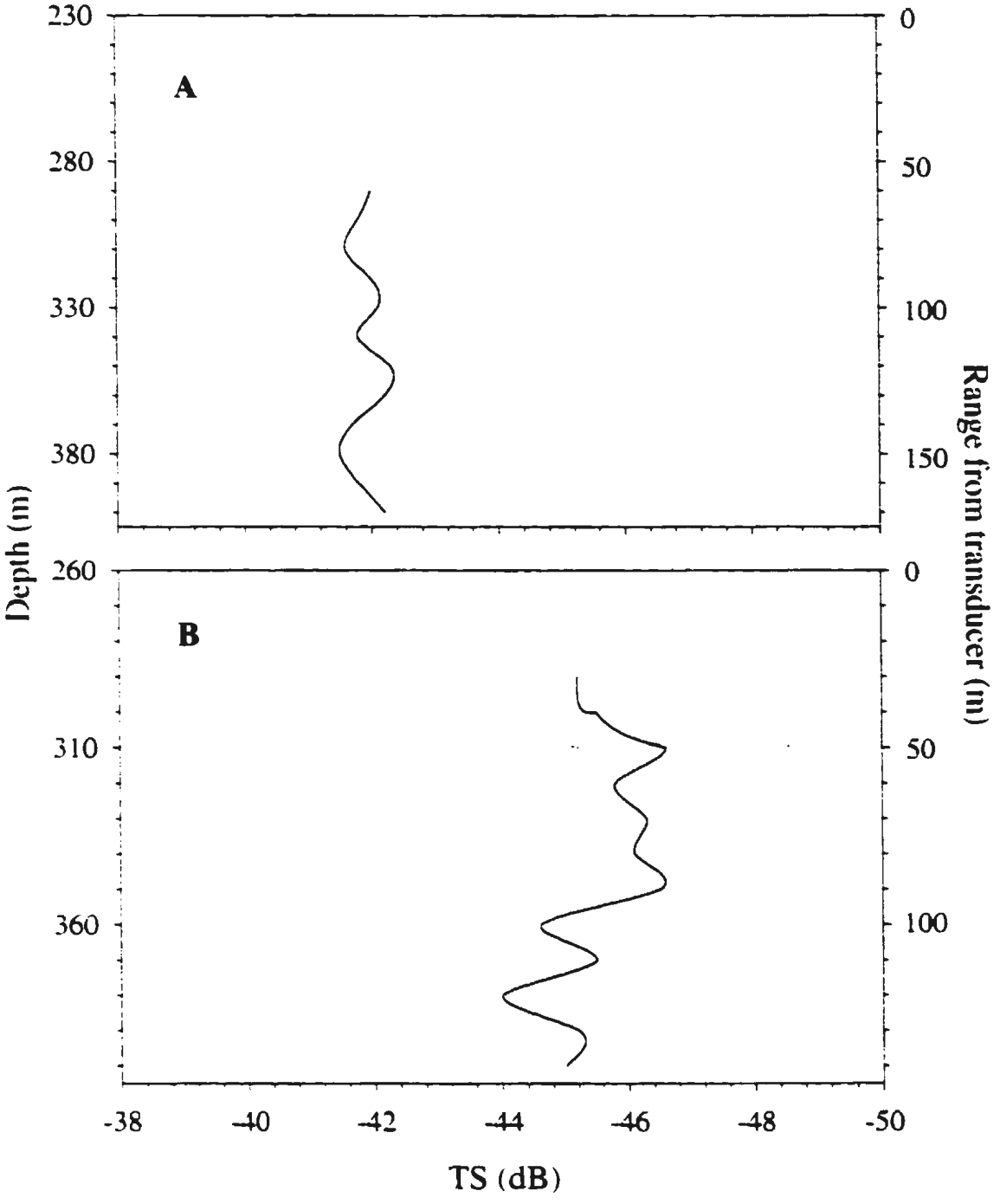
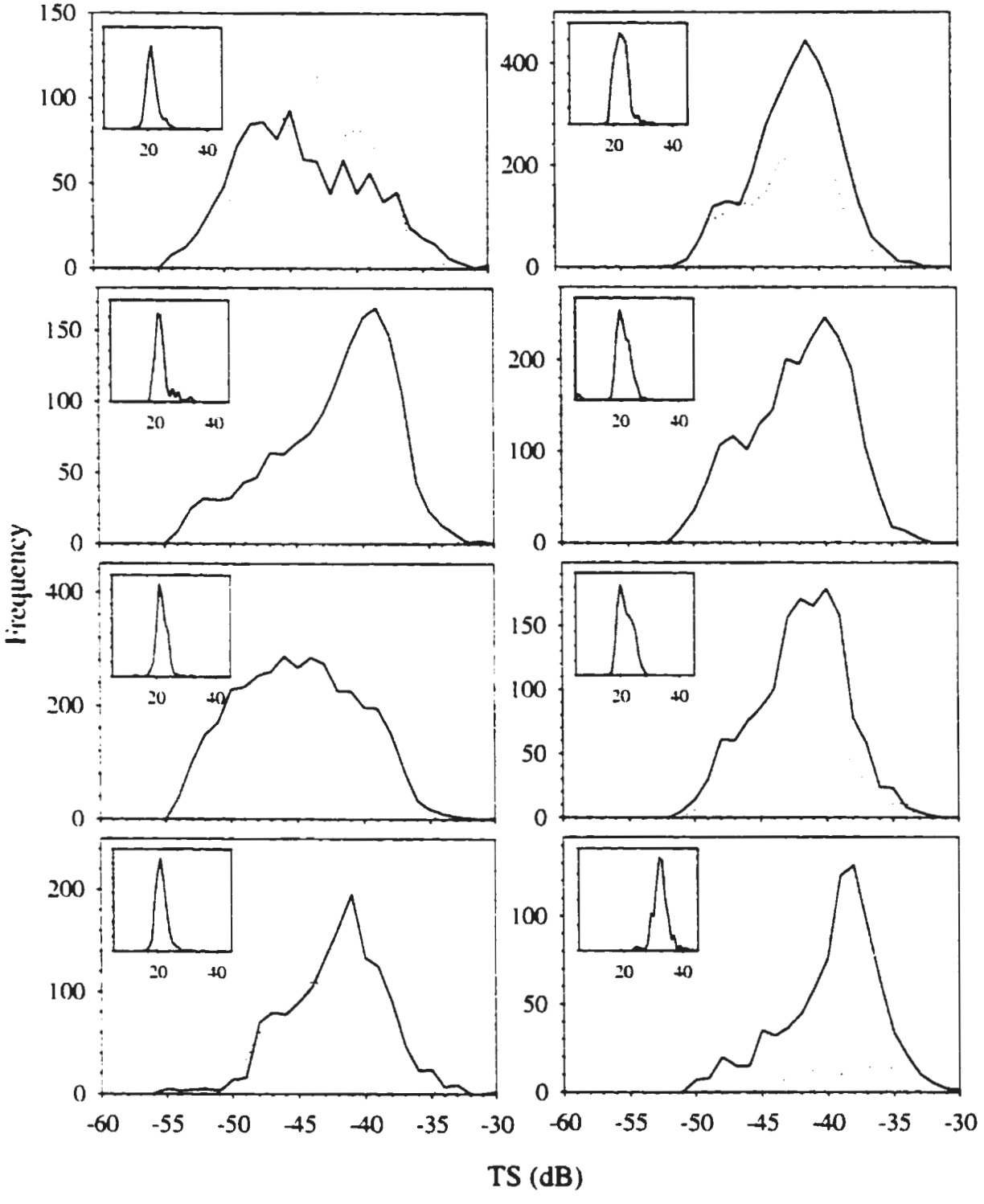


Figure 5.9. TS in dB (bounded by the SD) for the same redfish aggregation measured at two transducer depths A) 230 m and B) 260 m. The horizontal dotted line represent the 50 m range from transducer

Figure 5.10. TS (dB) frequency distribution for eight redfish aggregations measured using the dual beam (plain line) and split beam (dotted line) techniques. The inset windows represent the length frequency distribution (cm) at each site.


Frequency
TS (dB)
-60
-55
-50
-45
-40
-35
-30
20
40

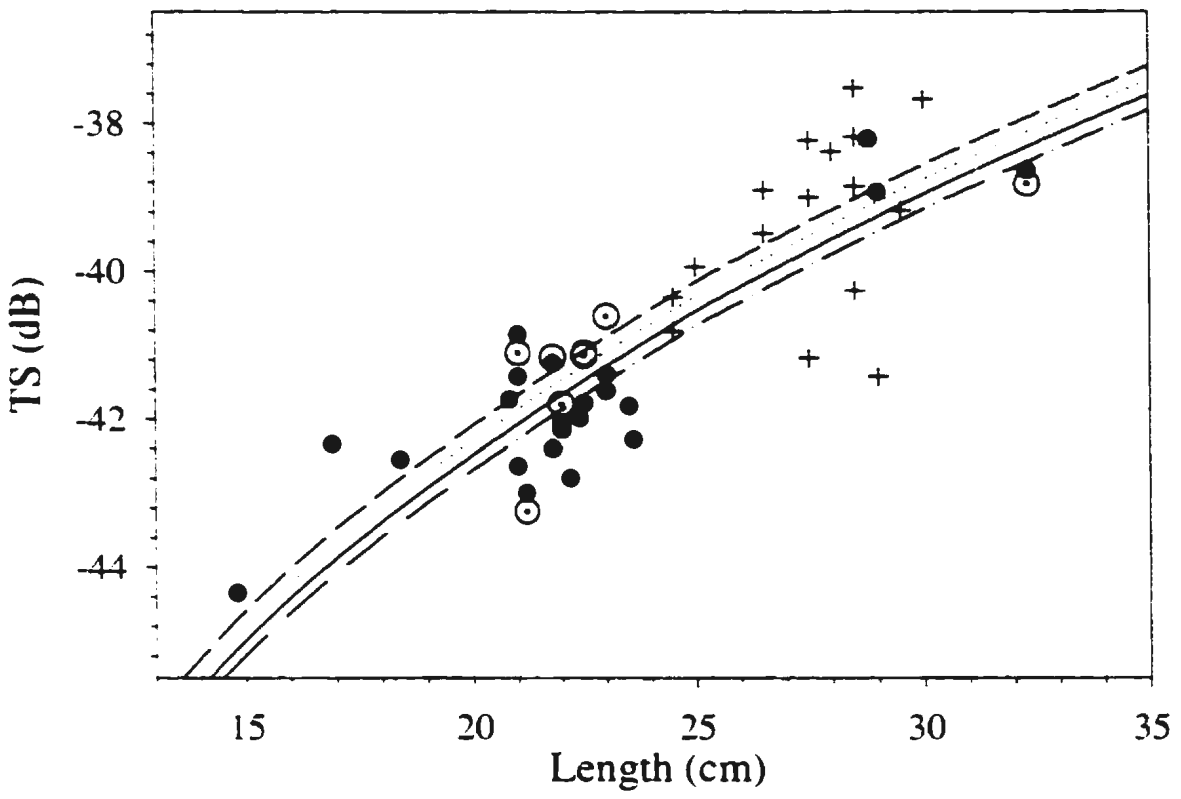


Figure 5.11. Mean TS (dB) and mean length (cm) for redfish measured *in situ* using the split beam (closed circles) and dual beam (dotted circles) techniques. Each point represents an experiment in which $N_v < 0.04$. The sample size for each point is given in Table 5.1. Crosses represent mean values for individual encaged fish measured with a split-beam system (Gauthier and Rose, in press).

Unbroken line: TS (dB) = 20 log[length (cm)] –68.5 (*In situ* data only)

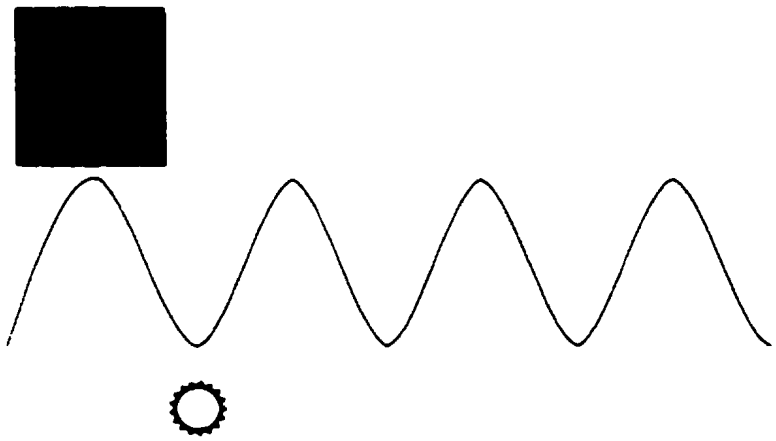
Broken Line: TS (dB) = 20 log[length (cm)] –68.1 (*Ex situ* data only)

Dotted line: TS (dB) = 20 log[length (cm)] –68.3 (*In situ* and *Ex situ* data)

Broken and dotted line: TS (dB) = 20 log[length (cm)] –68.7 (Weigthed *In situ** and *Ex situ* data)

* the weighted *in situ* data only has the same intercept

Chapter 6. An hypothesis on endogenous hydrostasis in Atlantic redfish (*Sebastes* spp.)



6.1 Abstract

I propose the hypothesis that Atlantic redfish have an endogenous cycle in the secretion and resorption of swimbladder gas. To test this hypothesis, I measured the *in situ* acoustic target strength (TS) of redfish during diel vertical migration and found no effect of depth, which is inconsistent with Boyle's law. An *ex situ* experiment on an immobilized redfish indicated systematic changes in TS of approximately 2 dB at night when vertical migration occurs. The observed change in TS is consistent with a swimbladder volume change that would maintain redfish near neutral buoyancy throughout the range of their vertical migration.

6.2 Résumé

Je propose l'hypothèse que le sébaste de l'Atlantique possède un cycle endogène permettant la sécrétion et l'absorption de gaz dans la vessie natatoire. J'ai mesuré l'indice de réflexion acoustique (IR) *in situ* de sébastes pendant leur migration verticale et n'a trouvé aucunes variations avec la profondeur, ce qui est contraire avec la loi de Boyle. Une expérience avec un sébastes immobilisé dans une cage a indiqué un changement systèmatique de l'IR d'environ 2 dB pendant la nuit, lorsque la migration verticale a lieu. Le changement observé dans l'IR est en accord avec un changement de volume de la vessie natatoire qui permettrait au sébaste de maintenir une flottabilité neutre pendant leur migration verticale.

6.3 Introduction

It has been argued that the rates of gas secretion and resorption are insufficient to adjust for buoyancy change in fish that perform diel migrations (Harden-Jones and Sholes, 1985), and that physoclistic vertical migrators have neutral buoyancy only at the shallowest range of their migration, being negatively buoyant in deeper water (Alexander, 1972; Arnold and Walker, 1992; Tewinkel and Fleisher, 1998). Such buoyancy arguments based on Boyle's gas expansion law suggest that acoustic target strength measures should change systematically over the migration depths. It was observed that Atlantic redfish (*Sebastes* spp.) may migrate 10-100 m or more vertically within a short period without concomitant change in TS. Daily inflation and deflation of the swimbladder has been observed in physostomous clupeiformes larvae (Hunter and Sanchez, 1976; Hoss et al., 1989; Uotani et al., 2000) that swallow air at the surface. In this paper I develop the hypothesis that the apparent stability in Atlantic redfish may depend on an endogenous rhythm in the secretion and resorption of gas from the swimbladder.

6.4 Materials and methods

In January 1997, a large redfish aggregation at 350 m depth was acoustically monitored for a 24 hr period on the edge of the Green and Grand Banks of Newfoundland (Nafo div. 3Ps). TS of individual fish was measured *in situ* using a calibrated hull-mounted EK-500 split-beam system operating at 38 kHz. Fish were sampled using a

Campelen 1800 bottom trawl and Diamond IV midwater trawl. To avoid the inclusion of multiple targets, TS was obtained only for areas of low density (ca < 0.04 fish per sample volume, see Sawada et al., 1993). In August 1999 the target strength (TS) of a stationary Atlantic beaked redfish (*Sebastes* spp.) was measured overnight (the fish was immobilized in monofilament netting). Details of the method used to capture and keep the fish alive are described in Gauthier and Rose (2001). In brief, the fish was captured in shallow water (60 m), acclimated at 30 m depth for a period of 24 hrs and subsequently kept in an holding cage close to the acoustic measurement setup. All subsequent underwater operations were performed by autonomous SCUBA divers. The fish (total length of 28.5 cm) was alive and in good condition throughout the experiment. Postmortem examination revealed no apparent damage to the swimbladder and other internal organs. Mean and standard deviation of TS were expressed in the logarithmic form following arithmetic averaging of backscattering cross section for each 10 minutes.

6.5 Results and discussion

In situ TS measurement of redfish was not possible during the day, because redfish stayed close to the bottom in aggregations too dense to allow single target resolution. After darkness the fish migrated vertically up to 120 m off bottom. Overall mean TS was -41.8 dB and the mean length of the fish 22 cm. There was no apparent increase in TS for fish located higher in the water column (Fig. 6.1).

The overall mean TS for the immobilized fish was -38.6 dB. However, at approximately 23:00, TS declined to -40.3 dB (Fig. 6.2). The lower mean TS was maintained until just before 3:00, after which mean TS increased to -36.8 dB for the remainder of the night. These changes could not have been caused by changes in aspect, as the fish was immobilized. The observed changes in TS could be attributable to changes in physiological state. More than 90% of the backscatter of a fish is produced by the swimbladder (Foote, 1980). Hence TS change most likely can be attributed to change in the cross-sectional area of the swimbladder. One explanation for such change is an hydrostasis function triggered by an endogenous cycle. The gas gland could be entrained (or stimulated) to secrete and resorb gas within a diel cycle. The direction of the change of TS observed in the immobilized redfish is consistent with the often observed upward migration at night in these species, and suggests that resorption of gas in the bladder may occur as an adaptation to the decreasing pressure at shallower depths. Harden-Jones and Scholes (1981) calculated the limits of the free vertical range within which a physoclist could swim without any exceptional buoyancy problems and gas compensation. For Atlantic cod, a reduction of 27% and an increase of 55% of the pressure at the depth at which fish are in neutral buoyancy could be tolerated. The same authors estimated that vertical migration would induce a TS change of approximately 2 dB. Accordingly, the 2-3 dB change observed in the immobilized redfish would enable the maintenance of neutral buoyancy over a vertical range of approximately 35 m from a depth of 60 m and 160 m from a depth of 300 m. This is within the range of redfish migration at sea (unpublished data). To further examine the observed change in TS of the encaged fish,

the swimbladder model of Mukai and Iida (1996) was employed to predict TS variation under vertical migration. Mukai and Iida (1996) found that TS changed with pressure (hence volume) from depth A to B following a balloon model, assuming concentric contraction or expansion of the swimbladder:

(1) $$TS_B = TS_A + \left[\left(\frac{20}{3}\log P_A\right) - \left(\frac{20}{3}\log P_B\right)\right]$$

where P is pressure in atmospheres. Fish at our capture site migrated vertically from a depth of approximately 60 m to 40 m. Boyle's law states that (for equal temperatures):

(2) $$P_{60m} \cdot V_{60m} = P_{40m} \cdot V_{40m}$$

where P is the pressure in atmospheres and V the volume in ml. For a swimbladder volume of 40 ml at the bottom (approximately 5% of body volume (Bone et al., 1995), and consistent with observation of excised bladders), a fish would resorb and secrete 16 ml of gas to counter the effects of pressure between 60 m and 40 m:

(3) $$\frac{7_{atm} \cdot 40_{ml}}{5_{atm}} = 56_{ml}$$

For the fish encaged near the surface, with the same rates and mechanisms of resorption and secretion, this would yield a much larger volume (at least 44.4 ml). According to

equation 1, such change (equivalent to approximately a 2 fold variation in pressure or volume) would yield a 2.17 dB difference in TS. This is consistent with the experiment result.

Little information exists on the potential rates of secretion and resorption of swimbladder gas for redfish. However, Marshall (1960) indicated that the provision of sufficient gas to fill the swimbladder during and after downward migration of many bathypelagic species is unlikely, unless the gas gland could store oxygen in a combined form. For upward movements, Marshall (1960) suggested that the resorbent surface of the gland and the steep concentration gradient between the tensions of gases in the swimbladder and in the blood could keep pace with resorption.

The results of this study lead to the formulation of the hypothesis that redfish undergo an endogenous cycle in the resorption and secretion of swimbladder gas. The mechanism by which they would accomplish rapid gas exchange in the bladder remains uncertain. Under this hypothesis, the volume of the swimbladder (hence target strength) for fish that migrate vertically would be relatively constant over the migratory cycle, and not follow Boyle's law.

6.6 Acknowledgements

I thank the crew of the CCGS Shamook, D. Ivany, W. Hiscock and M. Norris for their assistance at sea, and J. Wheeler for loan of the compound platform. Funding came from the Canada Department of Fisheries and Oceans (Redfish Multidisciplinary Research Program) and the Natural Sciences and Engineering Research Council of Canada Industrial Chair in Fisheries Conservation.

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6.8 Figures

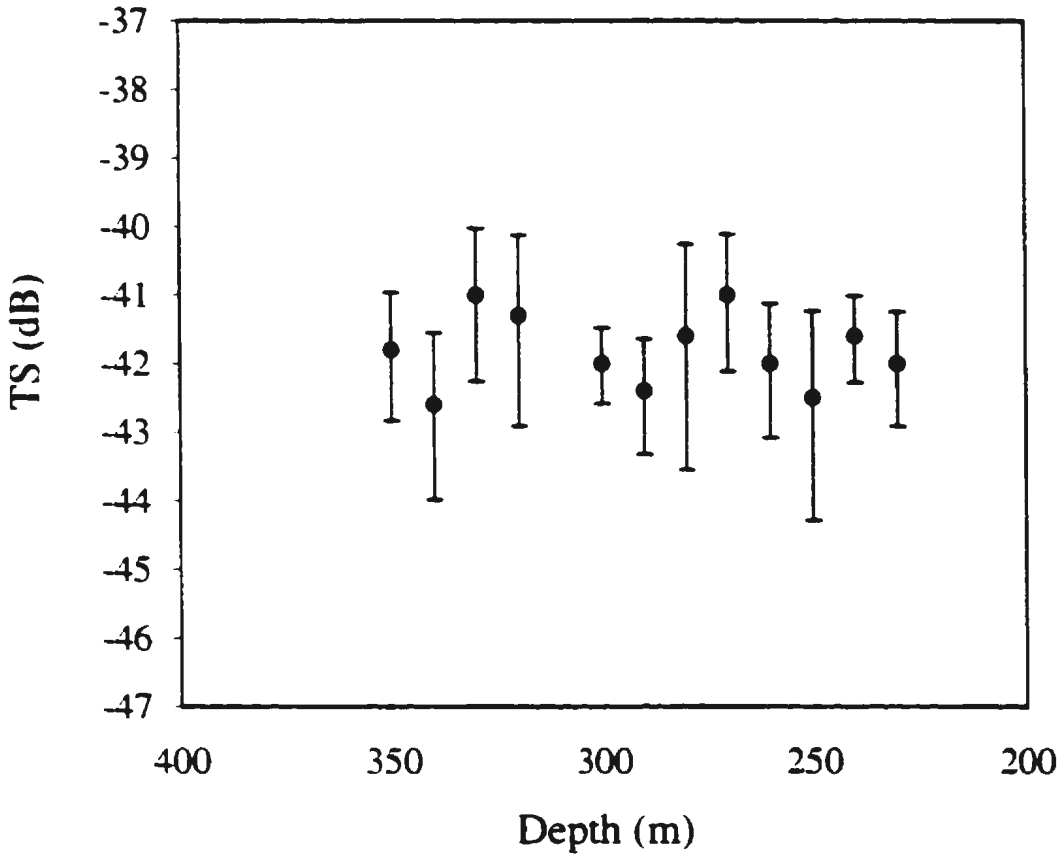


Figure 6.1. Mean (± SD) target strength of Atlantic redfish in 10 m depth strata during night-time migration from the bottom (total water depth = 350 m).

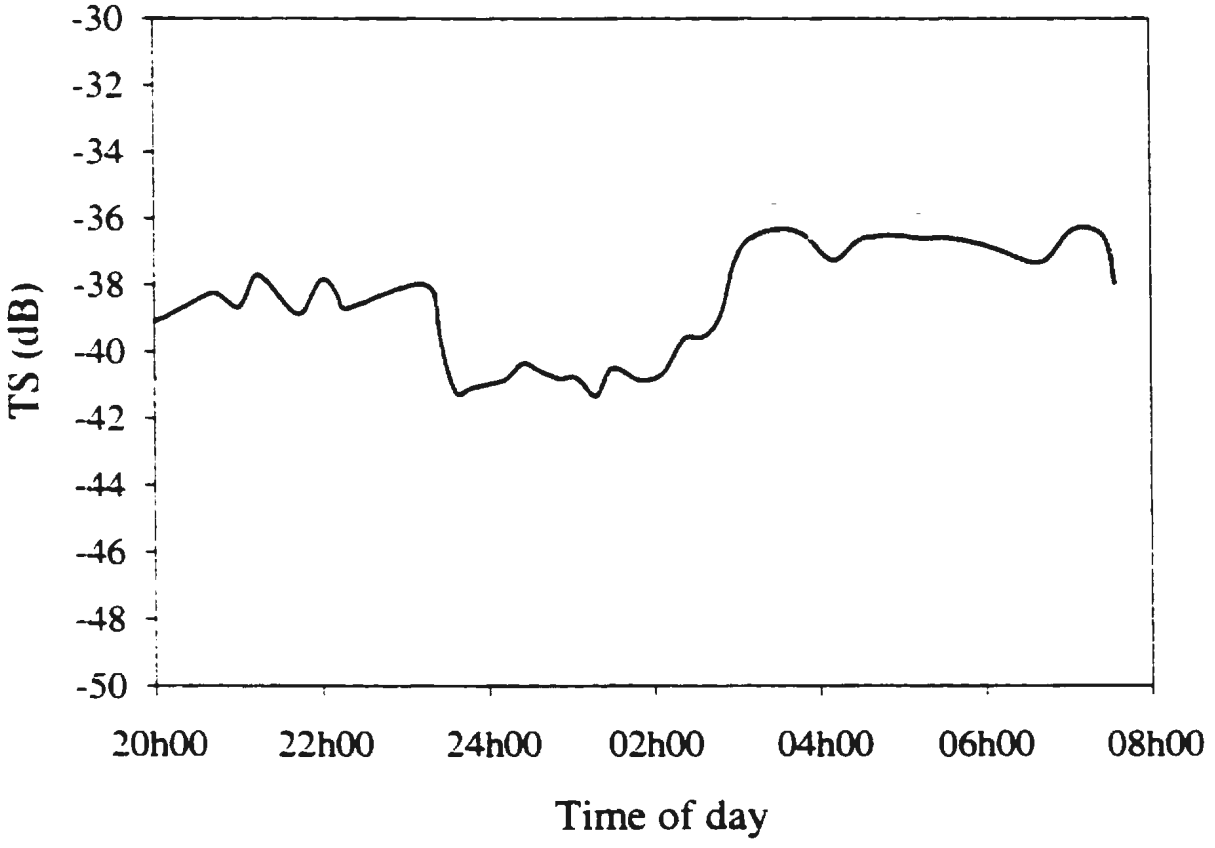
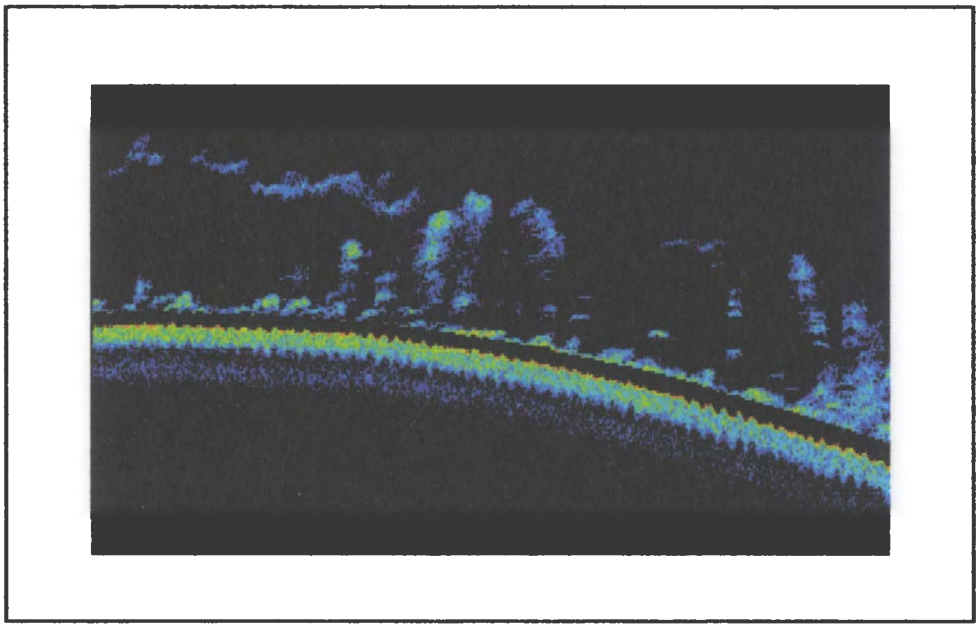


Figure 6.2. Mean target strength for an Atlantic redfish immobilized in dorsal aspect. bounded by the SD. Hours of total darkness were approximately 22h00 – 5h30.

Chapter 7. Acoustic observation of shoaling behavior and diel vertical migration in Atlantic redfish (*Sebastes* spp.).



7.1 Abstract

Acoustic methods were used to study Atlantic redfish (*Sebastes* spp.) vertical migration and shoaling behavior in Newfoundland waters. Redfish exhibited consistent patterns of vertical migration in winter, spring, and summer, which seemed to be limited by hydrostatic pressure. Vertical migration appeared to be a foraging strategy, in which redfish followed the migration of their euphausiid prey. On average, larger redfish were found in deeper waters, although increased variance in size distribution was observed in shallow areas. Pelagic shoals exhibited high degrees of variability in size, shape and internal structure. Attempts to explain variations in shoal density and area with various features of shoal position and stucture failed. Within-shoal distance between nearest neighboring fish did not go below 1 body length. Pelagic aggregations were generally in close proximity of dense patch of redfish along the sea floor. During the night, fish distributions were more homogenous and predictable.

7.2 Résumé

J'ai utilisé des méthodes acoustiques pour étudier la migration verticale et les comportements d'agrégation du sébaste Atlantique (*Sebastes* spp.) dans les eaux de Terre-Neuve. Le sébaste a effectué des migrations verticales en hiver, printemps et été qui semblaient être limitées par la pression hydrostatique. La migration semblait être une stratégie de prédation, dans laquelle les sébastes suivaient la migration des euphausiacés. En moyenne, de plus gros sébastes se retrouvaient en eaux plus profondes, cependant la variance de la taille était supérieure dans les zones moins profondes. Les agrégations pélagiques (banc de sébaste) avaient beaucoup de variabilité au niveau de la taille, forme et structure interne. Des efforts pour expliquer ces variations ont échoués. La distance entre les poissons dans un banc n'est pas aller au dessous de 1 lonqueur du corps. Les agrégations pélagiques étaient généralement associées à de dense formation de congénères près du fond marin. Pendant la nuit, la distibution des sébastes était plus homogène et prévisible.

7.3 Introduction

Many commercially important demersal and semi-pelagic marine fishes exhibit vertical migration and are typically found close to the bottom during the day and more pelagically at night (Beamish, 1966; Woodhead, 1966; Turuk, 1973; Atkinson, 1989). The extent of these migrations in adult marine fish and the mechanisms responsible for them are poorly known, despite their major influence on survey results and interpretation of fisheries data (Petrakis et al., 2001). Vertical migration have been linked to predator avoidance, foraging, and the utilization of an energetic refuge with appropriate temperatures or currents (Neilson and Perry, 1990). Many of these species also exhibit highly variable shoaling behavior.

Atlantic redfish (*Sebastes* spp.) are widespread and important commercial fishes in the North Atlantic. Redfishes are semi-demersal fish that aggregate in small and large shoals and typically perform extensive diel vertical migrations (Templeman, 1959). In contrast with the high diversity of Pacific *Sebastes*, only 3 species of redfish are found in the Northwest Atlantic. The Atlantic redfish species are difficult to distinguish using external features, and hence have been managed as a single stock in most jurisdictions. Breder (1959) suggested that *Sebastes* form characteristic roundshaped aggregations or "pods" of hundreds to thousands of individuals. However, numerous studies in the Pacific Ocean have shown that several aggregation types may be encountered in *Sebastes* assemblages (Nagtegaal, 1983; Leaman et al., 1990; Kieser et al., 1993; Stanley et al., 1998). Little is known about the ecology of redfish diel migration, although Atkinson

(1989) suggested that redfish vertically migrated to follow their euphausiid prey.

Quantification of shoal structure and vertical movements of species such as redfish is difficult using traditional net capture techniques because nets sample only a small portion of the water column at relatively low resolution. Net techniques are also invasive and may influence distribution patterns. Acoustic methods are less invasive (assuming no boat or tow body avoidance), efficiently sample large volumes of water and provide high-resolution information on shape and distribution of fish schools (Fréon and Misund, 1999). Acoustic school descriptors have been used to classify fish species (eg., Rose and Leggett, 1988) and with the use of ancillary information, such methods can successfully classify species that have relatively similar pelagic schooling patterns (Lawson et al., 2001). Recent developments in image analysis techniques enable quantification of the internal structure of fish aggregations (Reid and Simmonds, 1993; Weil et al., 1993; Lefeuvre et al., 2000).

In this paper, I use acoustic methods to investigate the diel vertical migration and shoaling behavior of redfish in Newfoundland waters of the Northwest Atlantic. Acoustic assessments of distribution, density and aggregation characteristics are employed to examine the effect of distribution depth on vertical migration behavior, shoaling structure and size segregation, and the effect of fish gender and maturity on the diversity of the behavior observed. I then investigate possible links between observed variations and ecological (i.e. foraging, predation) and environmental factors (pressure, temperature).

Finally, I conduct an analysis of the internal structure of pelagic redfish aggregations based on theoretical aggregation patterns (Pitcher, 1979) and observed acoustic properties.

7.4 Material and methods

A series of acoustic-trawl experiments were performed on large aggregations of redfish on the outer edge of the Green and Grand Banks of Newfoundland in July 1996, January 1997, and March-April 1998 (Fig. 7.1), from the Canadian Coast Guard Research vessel Teleost equipped with a 38 kHz Simrad EK500 split beam echosounder. The transducer had a 7.1° beam angle between half power points and a pulse width of 0.8 ms was transmitted every second over 24 hr periods along repeated transects. Full calibration following recommended procedures was performed at the beginning of each sea trip (Foote et al., 1987). A Campelen 1800 bottom trawl and midwater trawls (Diamond-9 in 1996, IYGPT in 1997-1998) were used to catch fish species and to estimate size composition at each site (Table 7.1). Other fish captured at the studied sites were generally benthic, namely Atlantic halibut (*Hippoglossus hippoglossus*), American plaice (*Hippoglossus platessoides*), witch flounder (*Glyptocephalus cynoglossus*) and skates (*Raja* spp.). These species most likely did not contribute significantly to the acoustic signal, since they have no swimbladder and are usually located in the acoustic dead zone. Experiments were rejected if Atlantic cod (*Gadus morhua*), hake (*Merluccius bilinearis*), haddock (*Melanogrammus aeglefinus*), or pollock (*Pollachius virens*) represented a

significant proportion of the catch (> 20 % by weight). Such catch results were rare (< 10 % of sets). The length, weight, gender and maturity were measured on a haphazard subsample of 200 to 500 redfish from each fishing set. For each sea trip, 20 to 50 stomachs were qualitatively examined to determine diet. Quantitative measurements were not possible because most sampled fish had everted stomachs. Stomachs of potential predators of redfish were examined when present. After each fishing set, bathymetric temperature and salinity profiles were obtained using a Seabird 2.5 vertical CTD cast.

Several measures of redfish distribution were made from the acoustic record. Identification was based on a combination of visual echogram assessment and catch data analysis. The minimum and maximum distance of fish above the ocean floor were assessed over the diel cycle. The pressure ratio ($\bar{P}$, in atmospheres) between the maximum and minimum pressure experienced was calculated as:

(1) $$\bar{P} = \frac{P_{max}}{P_{min}}$$

where P_{max} is the pressure at the bottom and P_{min} is the pressure at the upper range of migration.

The volumetric density of fish was estimated using the acoustic spherical scattering

strength (above a threshold of –75dB) obtained from the split-beam and the backscattering cross sections (σ_{bs} in m^2). The mean volume spherical scattering strength given by the SIMRAD EK500 was in logarithmic form:

(2) $$\dot{S}_v = 10\log_{10}\dot{s}_v$$

where $\dot{s}_v$ was calculated as:

(3) $$\dot{s}_v = \frac{\sum \sigma_{sp}}{V}$$

in which V is the volume in m^3 and σ_{sp} is the spherical scattering cross-section in m^2. The backscattering cross-section (σ_{bs}) is related to the spherical scattering cross-section (σ_{sp}) using the following equation:

(4) $$\sigma_{bs} = \frac{\sigma_{sp}}{4\pi}$$

it ensues that the volumetric density of fish (D_v in fish · m^{-3}) can be estimated as:

(5) $$D_v = 4\pi\frac{\dot{s}_v}{\hat{\sigma}_{bs}}$$

where $\hat{\sigma}_{bs}$ is the mean backscattering cross-section for a given fish species and size. The mean backscattering cross-section ($\hat{\sigma}_{bs}$) for redfish was derived from an empirical relation between the acoustic target strength (TS in dB) and mean length of fish (Gauthier and Rose, 2001):

$$\hat{\sigma}_{bs} = 10^{TS/10} \quad (6)$$

where TS (dB) = 20 Log [Length (cm)] –68.7

To document vertical migration of smaller organisms (mostly euphausiacea as interpreted from mid-water trawling), the average acoustic backscatter (thresholded at –125 dB) was measured in 10 m depth layers from the transducer (hull mounted at a depth of approximately 6 m) to the detected bottom. Measurements were made adjacent to but outside redfish aggregations to exclude fish echoes.

7.4.1 Shoaling behavior

The acoustic record was also used to describe and quantify shoaling behavior. Shoaling patterns were classified in three main groups: 1) dense aggregations having continuous contact with the ocean floor, 2) discrete pelagic shoal (no contact with ocean floor), and 3) dispersed pelagic shoals. The first two groups appeared as continuous

acoustic units (no possible discrimination between individuals) whereas single fish were distinguishable in the latter. The FASIT analytical software was used to measure a series of variables from each pelagic shoal encountered (LeFeuvre et al., 2000). For each shoal, I measured the dimensions (area, width and height), the average depth and distance off bottom, the average, minimum and maximum fish density inside the shoal and the ratio of average to maximum density (index of heterogeneity). The horizontal width of a shoal was measured as:

$$W = W_{echogram} - 2\tan\theta_{\frac{1}{2}}\left(\frac{r_{max} + r_{min}}{2}\right) \quad (7)$$

where $W_{echogram}$ is the measured width of the school in m, θ the half power angle of the acoustic beam in radians, and r_{max} and r_{min} are the range in m at the furthest right and left point of the school (LeFeuvre et al., 2000). The height of the shoal was measured by subtracting half the pulse length from the observed height on the echogram:

$$H = H_{echogram} - \left(\frac{c\tau}{2}\right) \quad (8)$$

where c is sound speed in water in ms^{-1} and τ is the pulse duration in seconds.

In an attempt to explain observed variations in the concentration of fish within pelagic shoals (volumetric density) or the size of pelagic shoals, general linear models

with a stepwise inclusion of variables were used. Several parameters and school statistics were entered as independent variables:

(9) $$\overline{D}_v = A + Alt + d_{shoal} + s_v^P$$

Where $\overline{D}_v$ is the mean volumetric fish density in the shoal (fish · m^{-3}), A is the area of the shoal in m^2, Alt is the mean altitude of fish above the bottom in m, d_{shoal} is the mean depth of the shoal in m, and s_v^P is the average volume spherical scattering strength (thresholded at –90 dB) in the pelagic zone, in the 2 m adjacent to the shoal margins. This measure provided a relative index of the density of pelagic scatterers, i.e. potential prey in the vicinity of the shoal. Alternatively, I also tested the model:

(10) $$A = \overline{D}_v + Alt + d_{shoal} + s_v^P$$

7.4.2 Distribution of fish within pelagic shoals

Acoustic densities were used to calculate the mean nearest neighbor distance (NND) between fish and the volume occupied by single fish inside each pelagic aggregation. For these analyses, I assumed that discrete pelagic aggregations were schools, comprised of synchronized and polarized swimming fish (Pitcher, 1983; Pitcher and Parrish, 1993). In detailed analysis of the position of neighboring fish, Pitcher and Partridge (1979) found that no one bearing was preferred over another (i.e. icosahedral,

cubic lattice, or diamond formation). In this analysis, I assumed that fish maintained a consistent NND while packing into a minimum volume. The volume (V_f) per individual was estimated based on the acoustic estimate of fish density. The mean free space around a fish was subsequently matched to an oblate spheroid with 3 main radii (x, y, z) on the fore and aft, lateral and vertical axe from a reference point on the fish (Fig. 7.2). The volume per fish (V_f) was consequently:

(11) $$V_f = 0.5\left(\frac{4\pi}{3}xyz\right)$$

The ratio of length to breadth to height of free space around each reference point was set to 1.5: 1: 1 (Pitcher and Partridge, 1979). Consequently, the mean vertical and lateral NNDs (representing the minimum NND) were:

(12) $$y \text{ (or } z) = \sqrt[3]{\frac{V_f}{\pi}}$$

The x coordinate could be obtained by multiplying y (or z) by 1.5. Values were expressed as body length (BL) by dividing the x, y, and z NNDs by the mean fish length obtained from the catch.

7.5 Results

7.5.1 Shoaling behavior and diel vertical migration

Redfish exhibited strong diel patterns in distribution (Fig. 7.3). During the day, fish were either in packed aggregations in direct contact with the detected acoustic bottom or in dense pelagic shoals close to the bottom. At dusk, pelagic shoals (when present) or individual fish tended to move higher in the water column, where eventually they dispersed throughout the pelagic zone for the night. At dawn, fish formed tight aggregations and returned close to the ocean floor. These patterns were relatively similar over the three years and seasons (winter, spring, summer) of experiments. However, in January 1997 no pelagic shoals were observed. Fish were on the bottom during the day and dispersed in the water column at night, with no apparent pelagic shoal formation.

Measurement of volume backscattering strength just outside of the redfish aggregations revealed strong diel patterns (Fig. 7.4). During the day, backscatter was relatively weak, except near bottom. At sunset, scattering layers appeared to move up in the water column, sometimes to distances > 300 m from the bottom. Pelagic volume backscattering strengths were always higher at night than during the day. Pelagic trawl samples indicated that these scattering layers were composed mainly of euphausiacea species. The migration of redfish was concurrent with the movements of scattering layers, but was not as extensive. The maximum distance of fish above the ocean floor illustrates the diel pattern of redfish migration (Fig. 7.5). In every survey, diel migration coincided with sunset and sunrise. However, the maximum distance of fish from the bottom varied

considerably during day and night, in part explained by the depth from which fish migrated (Fig. 7.6a). Fish were recorded at greater distance above the bottom as depth increased (ANOVA $R^2 = 0.74$, DF = 1: 94, F = 270, $P < 0.001$). The best-fit linear regression had the form migration range (m) = 0.37 · Depth (m) –39.7. When transformed into relative change in pressure, the migration pattern appeared to be relatively constant over depth (Fig. 7.6b). The pressure ratio significantly increased with depth ($R^2 = 0.35$, ANOVA DF = 1: 94, F = 50.6, $P < 0.001$), however the changes were small, having a regression slope of 0.009 with an intercept of 1.

The temperatures at which redfish were found ranged from 5.1 to 8.2 °C at the bottom, with the exception of one site in January 1997 where temperatures reached 9.1 °C. During vertical migration, the change in temperature between the upper range of migration and the bottom was always within 2°C.

Mean length of redfish in fishing sets ranged from 12 to 33 cm (Fig. 7.7) and increased with water depth (length (cm) = 14.2 + 0.036 · depth (m), $R^2 = 0.47$, ANOVA DF = 1:40, F = 37, $P < 0.001$). Within fishing sets, the standard deviation of length (vertical bars on Fig. 7.7) decreased with depth ($R^2 = 0.37$, ANOVA DF = 1:40, F = 25.1, $P < 0.001$).

The proportion of female redfish varied among sea trips and seasons ($\chi^2 = 8.33$, DF = 2, $P < 0.05$) and was lowest in March - April 1998 (Table 7.2). However, at this

time a large proportion of individuals were of undetermined gender because of their small size and indistinct sexual organs. In July 1996, all males and females measured (N = 3755) were immature. In January 1997, 74% of the females had eggs present, but with no evidence of larvae formation at the time of capture and 51 % of the males had mature testes, indicating that they would spawn that year. Only 2 females and 3 males measured were spent (with residual larvae or milt in vas deferens). In April-March 1998, 26% of the males and 37% of the females were at an early stage of maturation, while the larger proportion of individuals were immature.

A total of 82 stomachs were inspected for content. Those stomachs were in good condition (not everted), but the presence of partially digested prey items in the throat and mouth of many individuals was indicative of regurgitation. Euphausiacea species represented more than 80% of the prey items identified. Several large specimens of cod or pollock of mean length > 70 cm were caught within redfish aggregations, and many of these large gadoids (≈ 41 %) had whole redfish in their stomachs.

7.5.2 Pelagic schools

A total of 251 pelagic schools were analyzed, 177 in July 1996 and 74 in March-April 1998. Mean fish length for the analyzed schools ranged from 16.0 to 32.4 cm, with most (>80%) in the range 20-26 cm. Most schools were observed between 8:00 and 13:00 h. Only a few were recorded in the afternoon (13:00 – 18:00) and none at night, as fish were dispersed in the water column. School dimensions and structures varied

considerably (Table 7.3). General shapes on the echogram ranged from circular, oval, vertically or horizontally elongated ellipsoids, and amorphous shapes with many appendages. None of the parameters tested explained a significant amount of the variation in the internal average school density or school area ($p > 0.05$).

Within-school density varied by more than 100 fold, while school area varied by more than 1000 fold. Mean and maximum within-school densities followed lognormal distributions amd differed by as much as 200 fold (Fig. 7.8). Following logarithmic transformation, maximum and mean within-school densities were strongly correlated ($R^2 = 0.62$, $P < 0.001$).

The overall mean nearest neighbor distance of fish within schools was 6.9 body lengths and highly variable. There were no significant relationships between within-school mean densities, mean fish size, and mean nearest neighbor distance ($P>0.05$). However, the nearest neighbor values calculated from the maximum observed within-school densities did not go below 1 BL (Fig. 7.9). As within-school maximum densities increased, nearest neighbor distances decreased and tended to become constant at values between 1 and 2 body lengths (left-hand side of Fig. 7.9). This limiting of NND occurred because mean fish size decreased with maximum densities above approximately 2 fish $\cdot m^{-3}$.

7.6 Discussion

The timing of the vertical migration in redfish coincided with the time of sunset and sunrise in all years and seasons, suggesting that light intensity played an important role in the onset of this behavior (Neilson and Perry, 1990). Vertical migration of redfish was accompanied by the dispersion of an acoustic scattering layer, composed mainly of euphausiids. Many species of euphausiacea exhibit patterns of diel vertical migration in the Northwest Atlantic (Roe, 1983), and represent an important part of redfish diet (Petersen and Riget, 1995; Gorelova and Borodulin, 1997; Gonzalez and Bruno, 1997). Limited analysis of redfish gut content, and the presence of substantial amounts of euphausiacea in the catch (both on the bottom during the day and in the pelagic zone during the night) suggest that redfish migration is a foraging strategy, where predators follow the migration patterns of their prey (Fortier and Leggett, 1983; Blader and Bulman, 1986; Sameoto, 1988). Furthermore, deep-sea fishes often depend on olfaction in combination with mechanoreception to capture their prey, and do not hunt visually as much as shallower water species (Blaxter, 1980). During the day, redfish were located in dense shoals close to the bottom. This aggregating behavior could be a default condition that keeps them in contact with their prey, or a strategy to reduce individual risks to predation (Pitcher and Parrish, 1993). At the study sites, large cod and pollock (when present) appeared to be actively foraging on redfish near the bottom. Casa and Paz (1996) documented the importance of redfish in cod diet in this region. Other known predators of redfish include Greenland halibut (Pedersen and Riget, 1992) and harp seals (Lawson et al., 1995). While vertically migrating, redfish did not cross steep thermal gradients,

suggesting that the migration was not controlled by energetic thermotaxis (Wurtsbaugh and Neverman, 1988; Clark and Green, 1991). However, during the day the ocean floor may act as an energetic refuge from ocean currents. Little is known about the patterns and velocities of water at the locations and scales of redfish aggregations in this study.

The maximum distance that redfish migrated off the ocean floor appeared to be partly regulated by hydrostatic pressure. The pressure at the upper range of vertical migration was never less than 67% of the pressure at the bottom. Redfish are probably feeding during their pelagic excursions and may benefit from quasi-neutral buoyancy. The range within which they can maintain neutral buoyancy may be a limiting factor for vertical movement (see chaper 6).

The presence, shape, and size of pelagic schools were all highly variable. Schooling likely depends on a visual response to conspecifics (Cushing and Harden-Jones, 1966). Redfish only formed schools during daytime. No schools were observed in January, when redfish were in an advanced state of maturation and females were less abundant than in July or April. Seasonal differences and interannual variability in school characteristics have been documented for several pelagic species (Fréon and Misund, 1999).

Several factors might bias the measurements of redfish shoals. The detection and sizing of very small shoals is limited by the use of a threshold (which affects marginal

detection) and the critical angle of detection. Kieser et al. (1993) demonstrated that the difference between the half power angle and actual critical angle could lead to substantial differences in estimating the cross-section width of small schools. The measurement of internal structure is affected by TS scaling and fish size. If fish size within a school varied systematically, my estimates of structural density would be biased. However, the observed size distributions were relatively narrow (a few cm). There is much evidence of size assortive shoaling in fish (Pitcher et al., 1985; 1986; Theodorakis, 1989; Ranta et al., 1992a; 1992b; Krause et al., 1996).

The data further suggest size segregation of redfish with depth. Interestingly, the standard deviation of redfish size was larger in shallower waters, suggesting that segregation was not as evident in shallower as in deeper waters. Increasing fish size with depth has been observed in other demersal fish such as hake (Gordua and Duarte, 1991).

Behavioral and evolutionary studies on schooling fish reveal that aggregation is more advantageous than solitary existence (Mangel, 1990; Parrish, 1992). The evolution and maintenance of aggregative behavior result from the constant pressure and balance of costs to benefits for individual fish. For schooling fish, the increase in intraspecific competition is outweighed by the benefits of lower individual risk to predation, greater access to food and foraging ability (search radius), and/or lower costs of swimming (Weihs, 1973; Turner and Pitcher, 1986; Magurran, 1990; Ryer and Olla, 1992). The spatial and time scales used to observe aggregative behavior will have a strong impact on

the perceived orientation and polarization of individuals. Consequently, schooling in a species does not necessarily imply a constant state of congregate formation and orientation, but rather that the individuals have the ability to adopt schooling patterns when warranted (Parrish and Turchin, 1997).

Attempts to explain variations in the internal mean density or area of pelagic schools were unsuccessful. None of the measured variables explained a significant portion of the observed variability. Such unexplained variability in school size and structure was also reported by Scalabrin and Massé (1993) from acoustic observations of fish shoals in the Bay of Biscay. Fréon et al. (1992) showed that the distribution of density inside tropical clupeid schools was highly heterogeneous, with many regions of very low and high density. Other studies on aggregations of pelagic species such as herring (*Clupea harrengus*), sprat (*Spratus spratus*), and saithe (*Pollachius virens*) have revealed variations in packing density of 100 fold or more, as observed in this study (Misund, 1993; Misund and Floen, 1993; Misund et al., 1995). It remains an open question as to whether variations in redfish school density and size are related to some unmeasured factor or simply random in nature. The spatial and temporal scales used to make the observations can also affect the interpretation of results.

Finally, my data indicated that redfish form pelagic aggregations with minimum NND of 1 BL. Pitcher and Partridge (1979) concluded that the volume per fish in a school could be approximated by the cube of body length. For redfish of 22 cm, this

would be equivalent to a packing density of approximately 94 fish · m^{-3}, which is much greater than the estimated mean density for this study. Serebrov (1976) reported that fish of a wide range of species occupied water volumes ranging from 3 to 12 L^3 (cube of the fish length) within a shoal. Such volumes would yield packing densities of approximately 8 to 31 fish · m^{-3} for redfish of 22 cm length, which is consistent with the maximum recorded densities. The low levels and high variability of density observed within the pelagic aggregations suggests that redfish do not form "schools", but rather comprise dense shoals where fish are not engaged in polarized and synchronized swimming (Pitcher, 1979). Our estimation of NND indicates average values somewhat higher than predicted by Partridge et al. (1980) on measurements of cod, saithe and herring. Their study indicated mean NNDs of approximately 0.4 to 0.8 BL. However, in high density of redfish shoals, NND tended to remain constant between 1 and 2 BL, suggesting that redfish maintain a minimum NND threshold proportional to fish size. Partridge et al. (1980) also concluded that the degree of organization within schools may depends partly on the behavioral nature of the species, and that cod exhibited more variability than saithe, which in turn exhibited more variability than herring. Many other elements can contribute to variability in the density and structure of fish schools in the wild. These include fish meneuverability (Partridge et al., 1980), variable swimming speed of individuals within the school (Holliday, 1977), individual excitement level and/or hunger (Morgan, 1988; Robinson and Pitcher, 1989a; 1989b; Robinson, 1995), and the light intensity (Hunter and Nicholl, 1985; Azuma and Iwata, 1994). Deblois and Rose (1995) observed that foraging activity influenced the density of cod shoals.

In conclusion, redfish have been shown to conduct regular vertical migration in concert with light cycles during winter, spring, and summer. The movements are likely feeding migration and are limited by pressure differentials. Vertical migration and the myriads of the aggregation types observed in this study and the variability in pelagic school structure are almost certain to impact the interpretation of both fisheries surveys using trawls and echosounders and data from redfish fisheries.

7.7 Acknowledgements

I thank the crew of the CCGS Teleost, C. Lang, R. Forward, W. Hiscock and G.L. Lawson for assistance at sea. Funding was received from the Canada Department of Fisheries and Oceans (Redfish Multidisciplinary Research Program) and the Natural Sciences and Engineering Research Council of Canada Industrial Chair in Fisheries Conservation at Memorial University of Newfoundland

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7.9 Tables

Table 7.1. Fishing gear specifications.

Part		Campelen 1800	Diamond IX	IYGPT
Trawl Doors		4.3 m^2 Poly-oval 1400 kg	6.0 m^2 Suberkrub 880 kg	4.0 m^2 Suberkrub 431 kg
Wings				
	Wingline	8.02 m	34.45 m	1.60 m
	Mesh size	80 mm	560 mm	100 mm
1st Belly				
	Ribline	10.59 m (forward)*	20.86 m	4.50 m
	Mesh size	80 and 60 mm	560 mm	100 mm
2nd Belly				
	Ribline	10.22 m (middle)*	30.65 m	5.00 m
	Mesh size	44 mm	406 mm	100 mm
3rd Belly				
	Ribline	19.98 m (aft)*	20.10 m	7.20 m
	Mesh size	44 mm	200 mm	80 mm
4th Belly				
	Ribline		11.45 m	4.00 m
	Mesh size		114 mm	40 mm
5th Belly				
	Ribline			2.40 m
	Mesh size			20 mm
Extension				
	Ribline		18.40 m	7.62 m
	Mesh size		46 mm	13 mm
Codend				
	Meshes deep	130 x 129 x 199.5	98 x 98 x 199.5	280 x 280 x 500
	Mesh size	44 mm	46 mm	13 mm

*Riblines for the Campelen extend beyond the bellies

Table 7.2. Number of males and females sampled in the three different sea trips. Percentage are given in brackets.

Date	Females	Males	Indeterminate
July 1996	1826 (48.5 %)	1919 (51.0 %)	19 (0.5 %)
January 1997	799 (38.8 %)	1256 (61.0 %)	4 (0.2 %)
March-April 1998	1943 (53.6 %)	1226 (33.8 %)	457 (12.6 %)

Table 7.3. Mean and range of the various acoustic school descriptor for surveys in 1996 and 1998.

School descriptor	July 1996 (N = 177)		March-April 1998 (N = 74)	
	Mean	**Range**	**Mean**	**Range**
Width (m)	106	1 – 2774	75	1 - 638
Height (m)	8	1 - 48	14	1 - 65
Area (m^2)	1137	23 - 38032	1134	25 - 7343
Distance off bottom (m)	22	5 - 85	17	5 - 55
Depth (m)	305	175 - 445	245	145 - 415
NND_{shoal} (m)	112	11 - 943	86	8 - 576
Pelagic scatterers ($m^2 \cdot 10^{-9} \cdot m^{-3}$)	7.9	2.5 – 25.3	8.2	2.6 – 27.1
Mean density ($fish \cdot m^{-3}$)	0.16	0.01 - 1.41	0.17	0.03 - 1.20
Minimum density ($fish \cdot m^{-3}$)	0.001	0.0002 - 0.006	0.001	0.0001 - 0.008
Maximum density ($fish \cdot m^{-3}$)	4.1	0.05 - 25.5	5.6	0.35 – 21.2
Mean NND (BL)	7.1	3.1 – 20.2	5.8	3.6 - 9.5
Minimum NND (BL)	2.9	1.1 - 8.43	2.2	1.1 – 5.4

Figure 7.1. Map of Newfoundland and Atlantic Canada. The circled area indicate the location of our redfish study area.

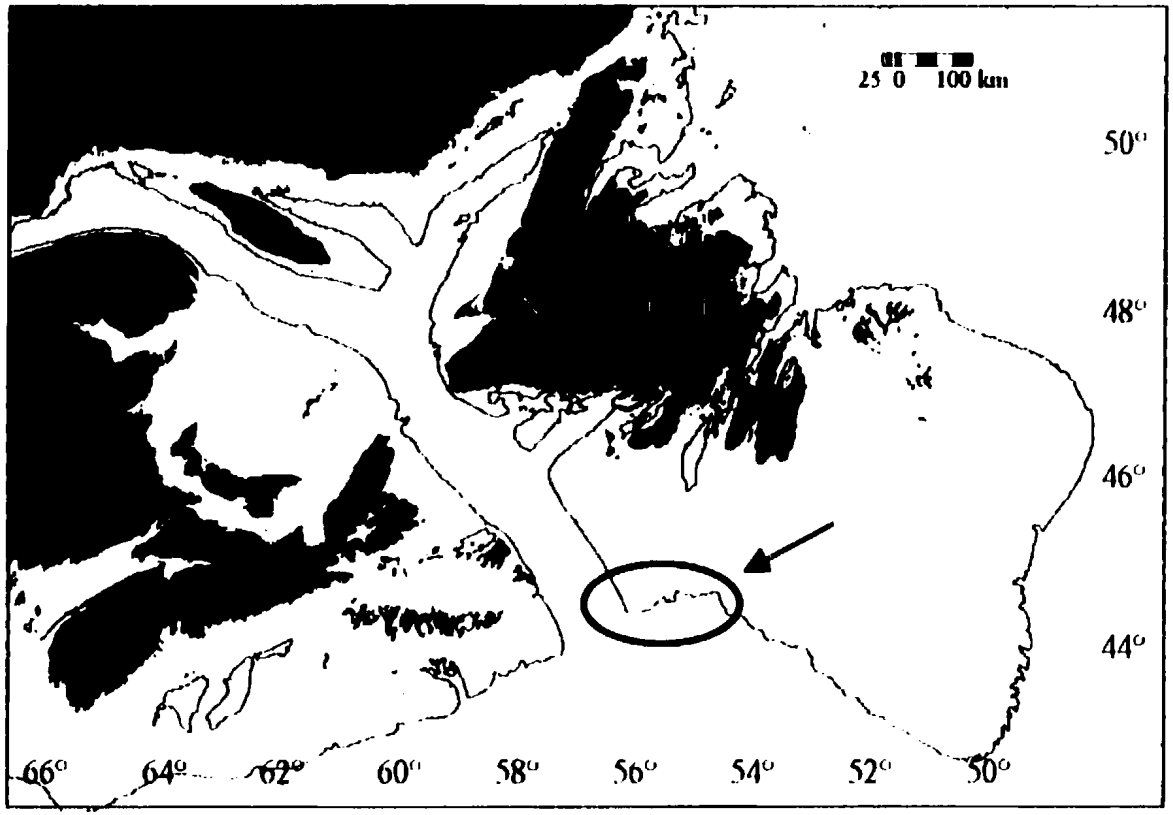

25 0 100 km
50°
48°
46°
44°
66°
64°
62°
60°
58°
56°
54°
52°
50°

Figure 7.2. Illustration of the free volume around individual fish, with the fore and aft (x), lateral (y), and vertical (z) coordinates.

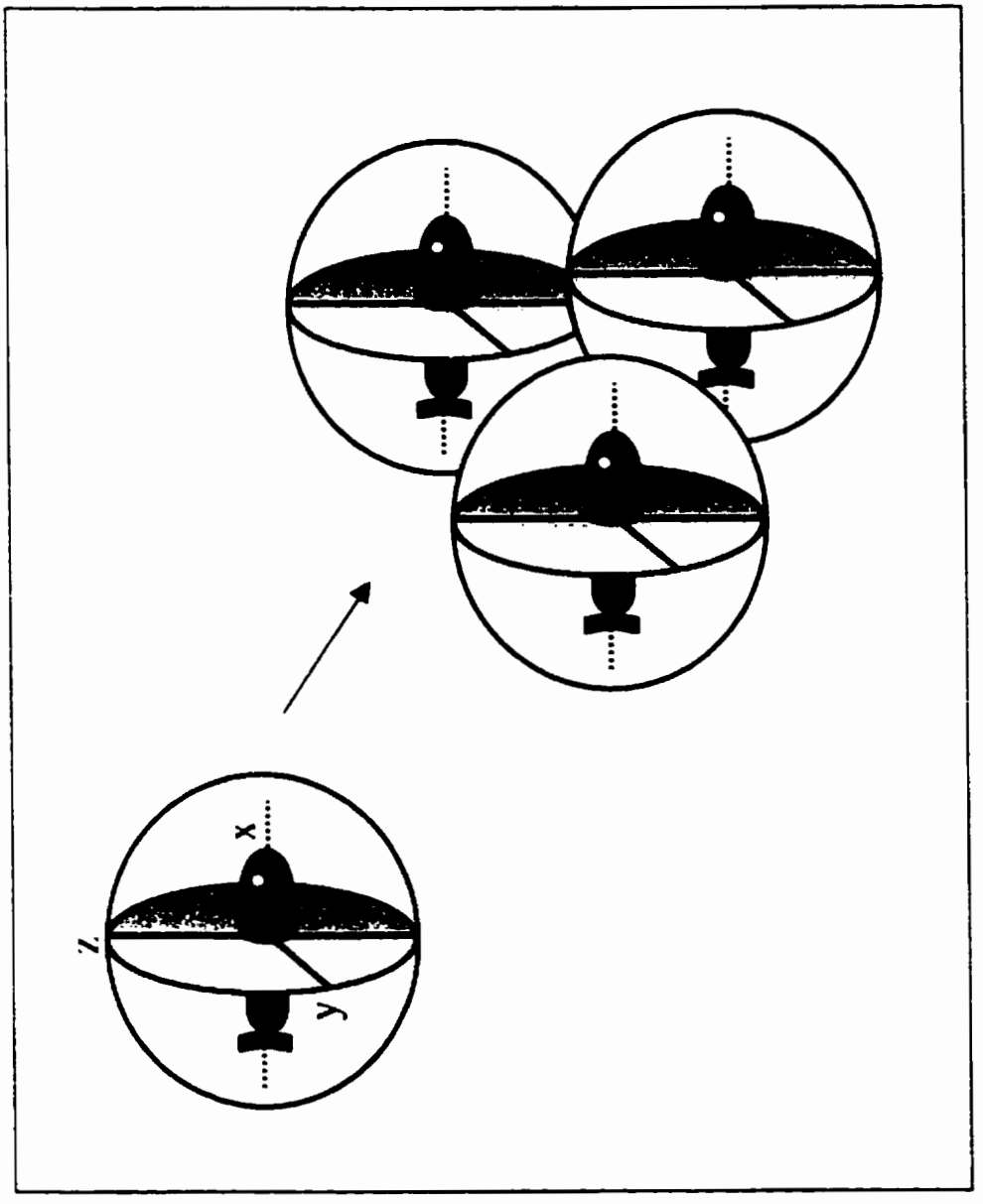

x
z
y

Figure 7.3. Echograms of typical redfish shoal structures observed along the same transect in April 1998: a) dense aggregations of fish on the bottom during the day, b) pelagic shoals near sunset and c) dispersed fish during the night.

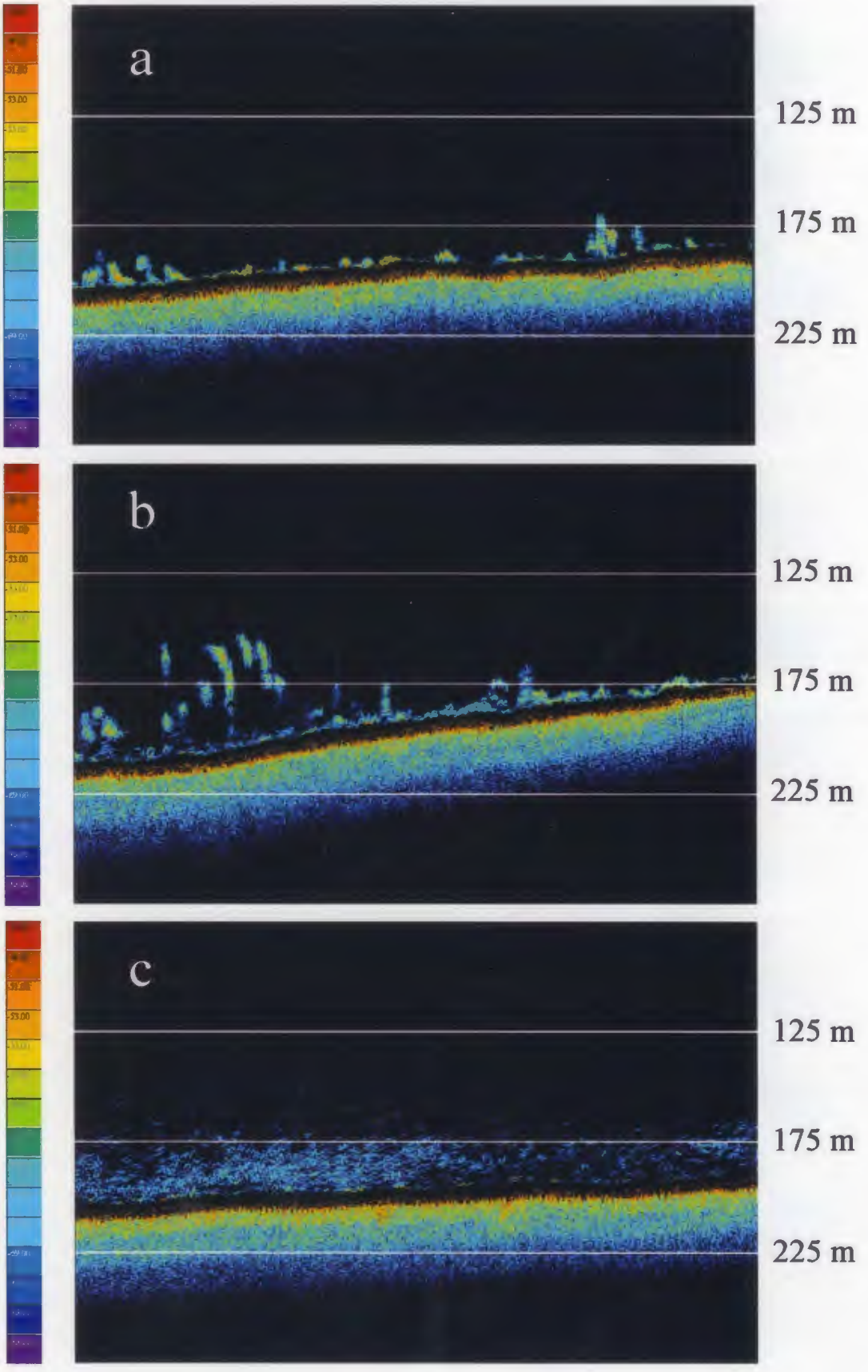

a
125 m
175 m
225 m
b
125 m
175 m
225 m
c
125 m
175 m
225 m

Figure 7.4. Representative depth profiles of acoustic volume backscattering strength (m^{-1}) measured next to a redfish aggregation during the day and the night.

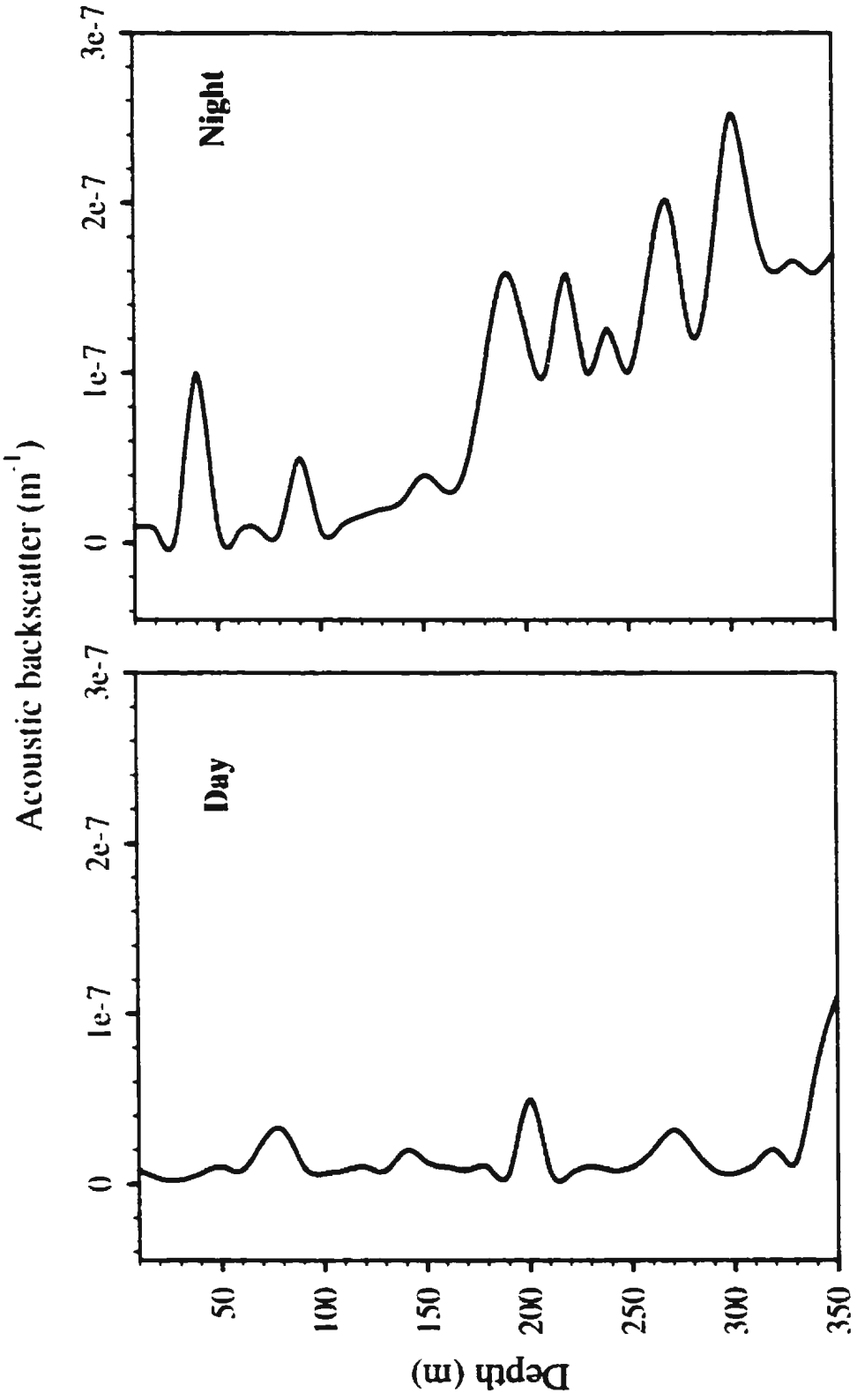
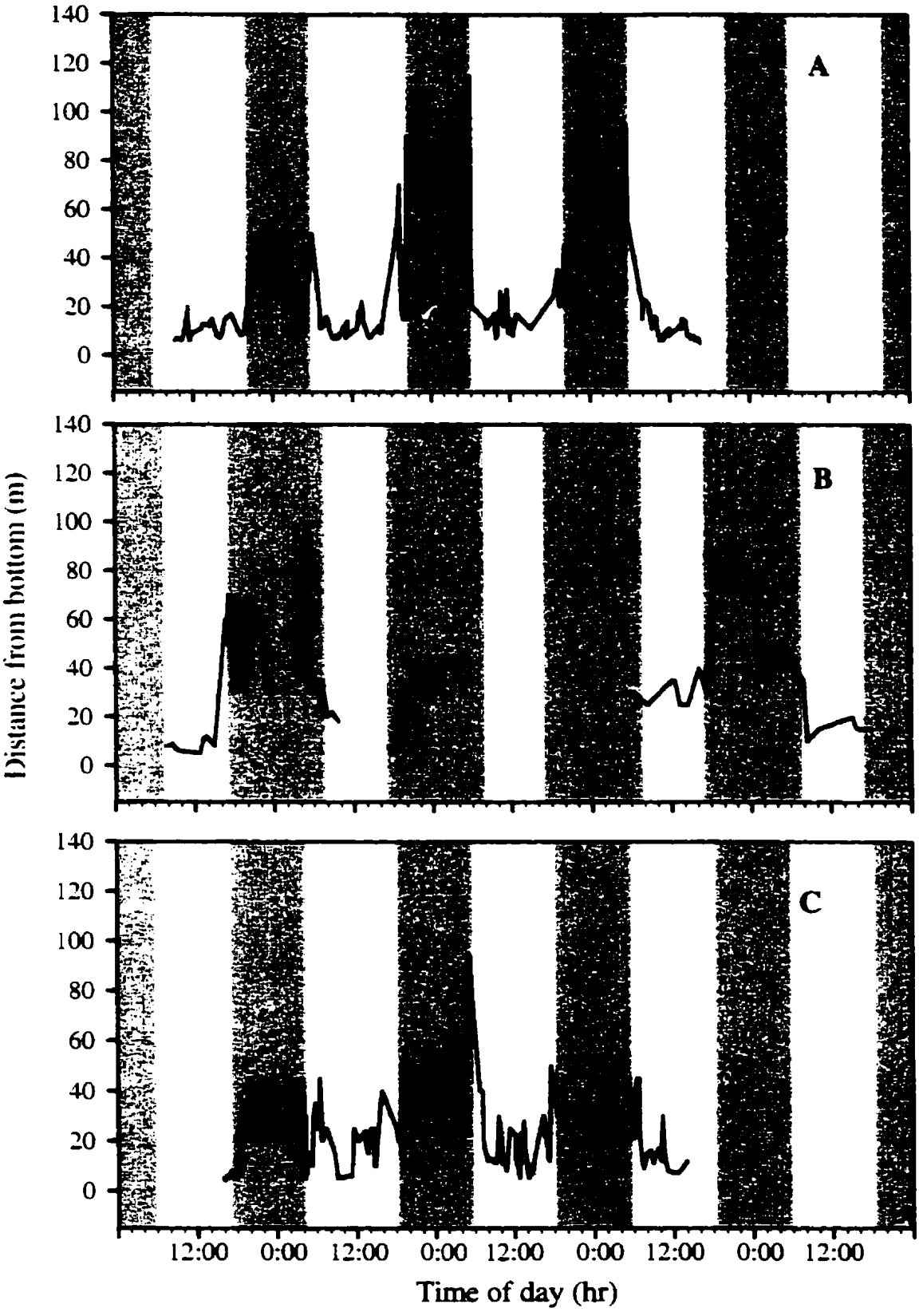

Night
Day
Acoustic backscatter (m-1)
0
1e-7
2e-7
3e-7
Depth (m)
50
100
150
200
250
300
350

Figure 7.5. Maximum distance of fish above the bottom for a) July 24-27 1996, b) January 10-14 1997, and c) March 30 – April 2 1998. The grey areas represent nights, delimited by time of sunset and sunrise (Newfoundland standard time). Sampling was interrupted twice in January 1997 due to bad weather conditions.


140
120
100
80
60
40
20
0
A
B
C
Distance from bottom (m)
12:00
0:00
12:00
0:00
12:00
0:00
12:00
0:00
12:00
Time of day (hr)

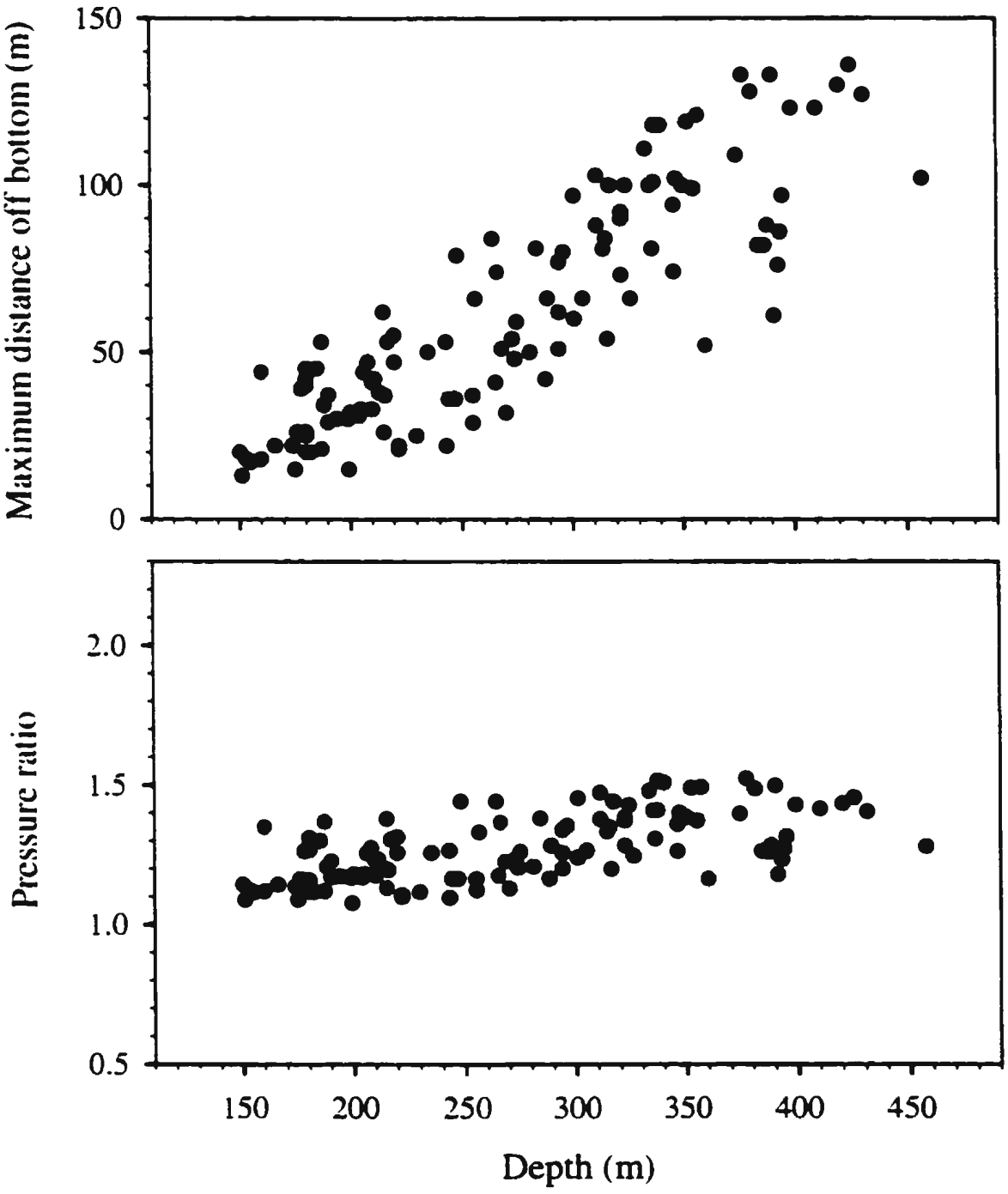


Figure 7.6. Migration of redish at different depths, expressed as the maximum distance of fish above the bottom (a) and ratio of the pressure (in atmospheres) at the bottom and at the maximum distance of fish above bottom (b).

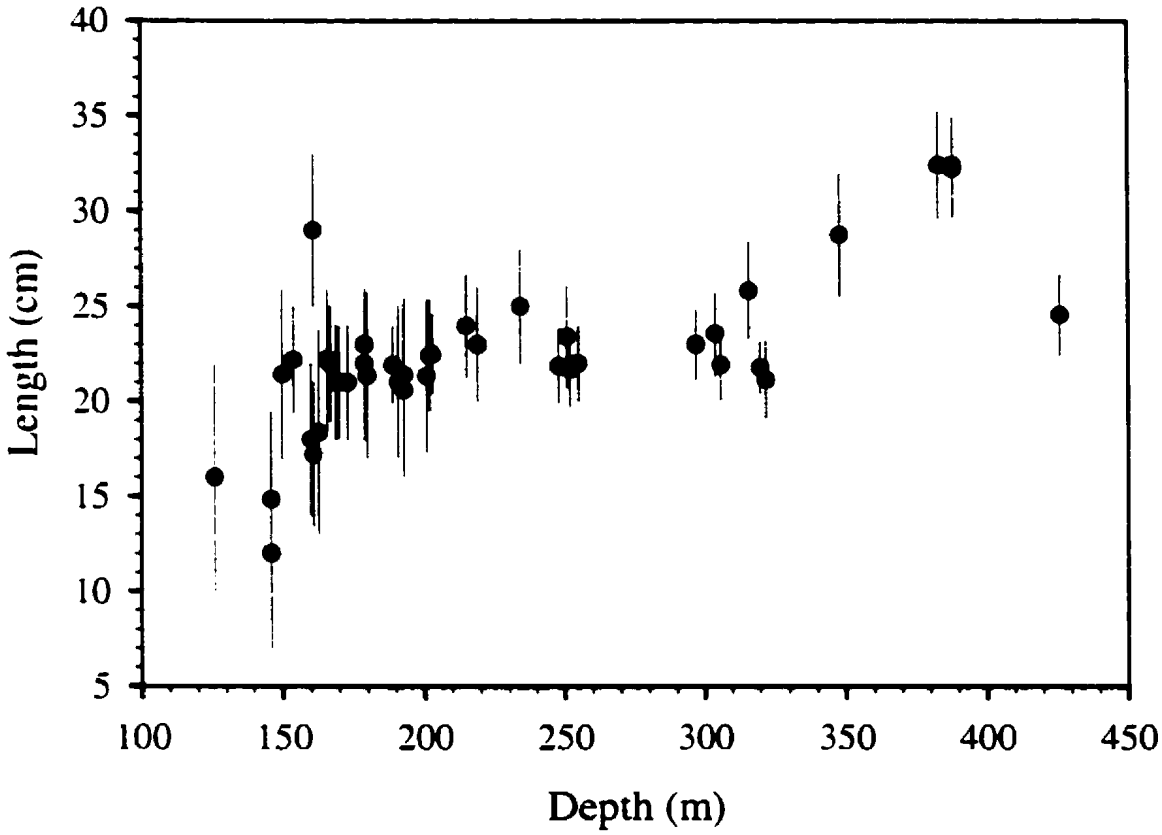
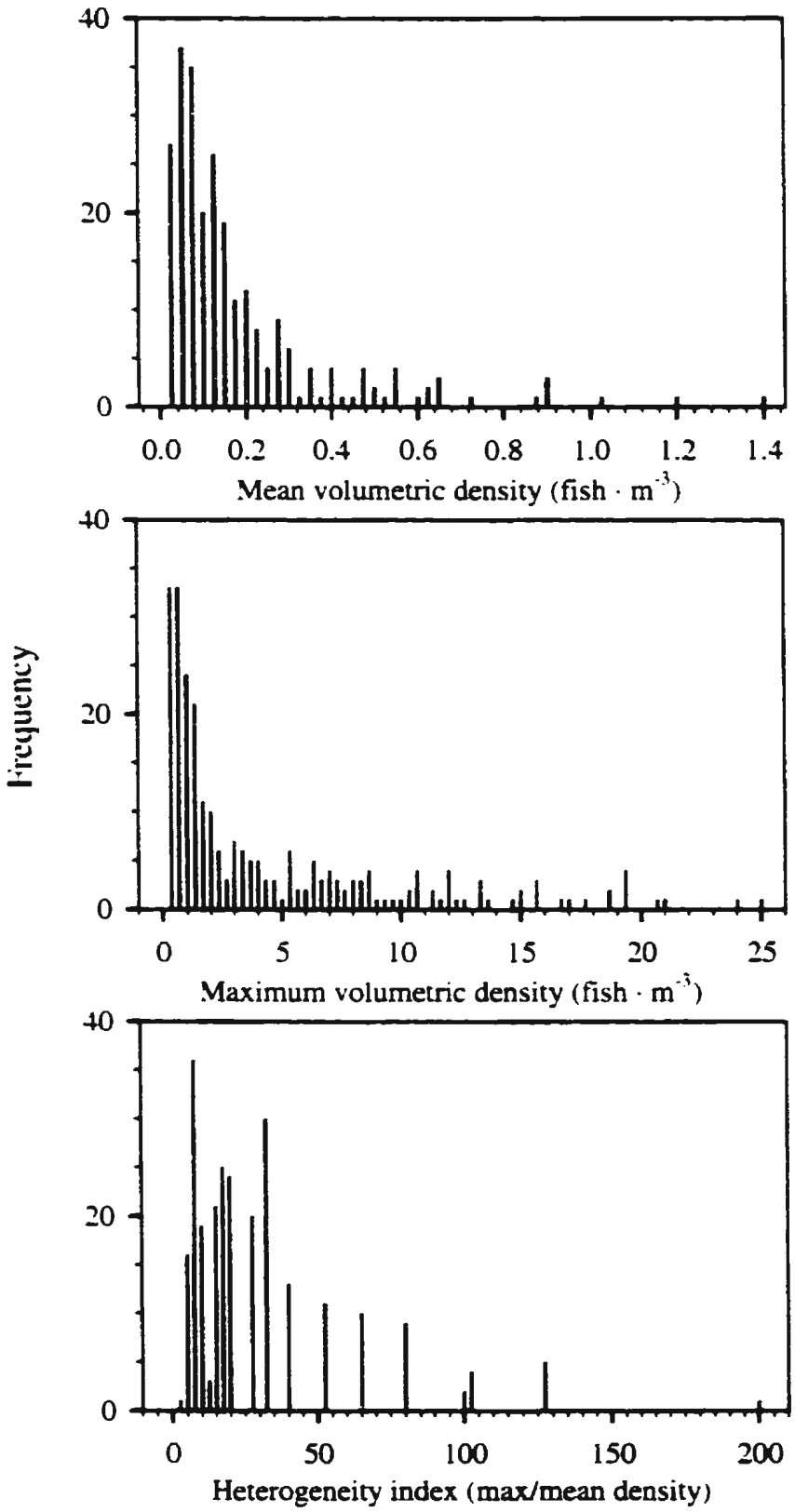


Figure 7.7. Mean length of redfish captured at different depth. Vertical bars represent standard deviation.

Figure 7.8. Frequency distribution of the mean (a), maximum (b) and ratio of mean to maximum (c) densities inside pelagic schools.


Frequency
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Mean volumetric density (fish · m-3)
40
20
0
0
5
10
15
20
25
Maximum volumetric density (fish · m-3)
40
20
0
0
50
100
150
200
Heterogeneity index (max/mean density)

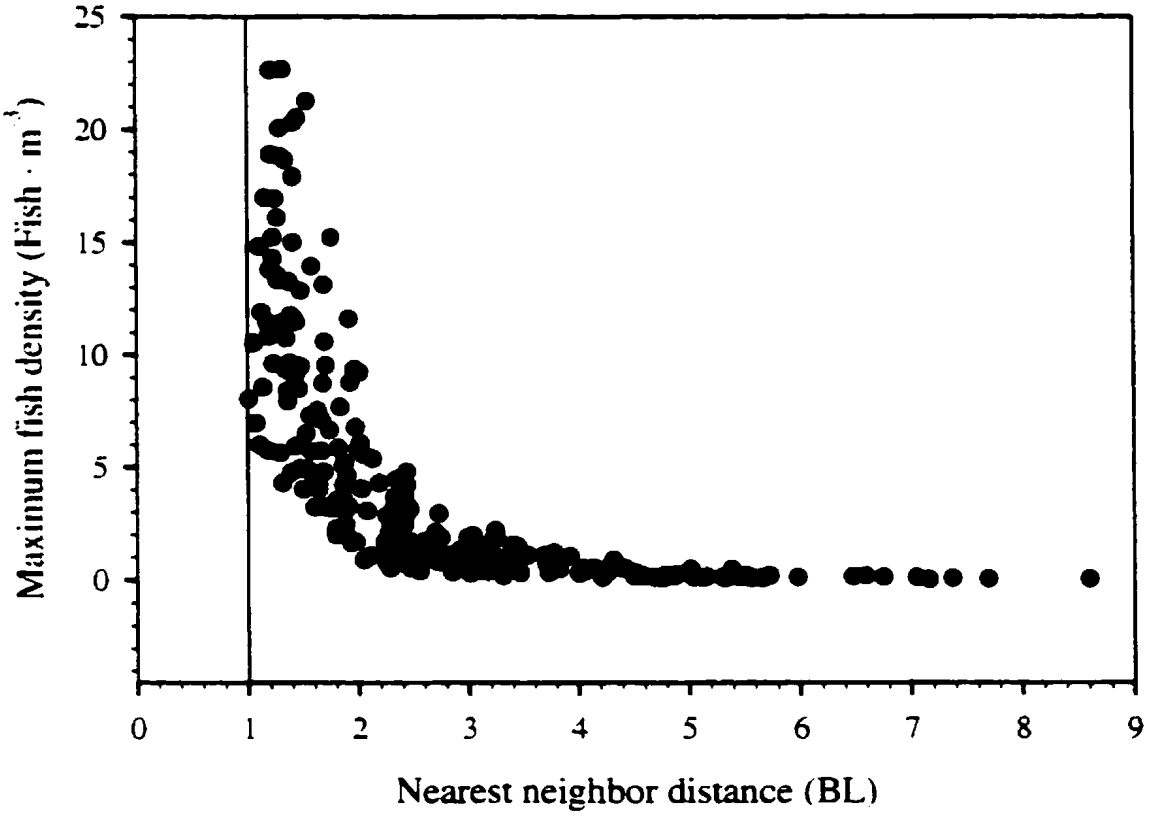
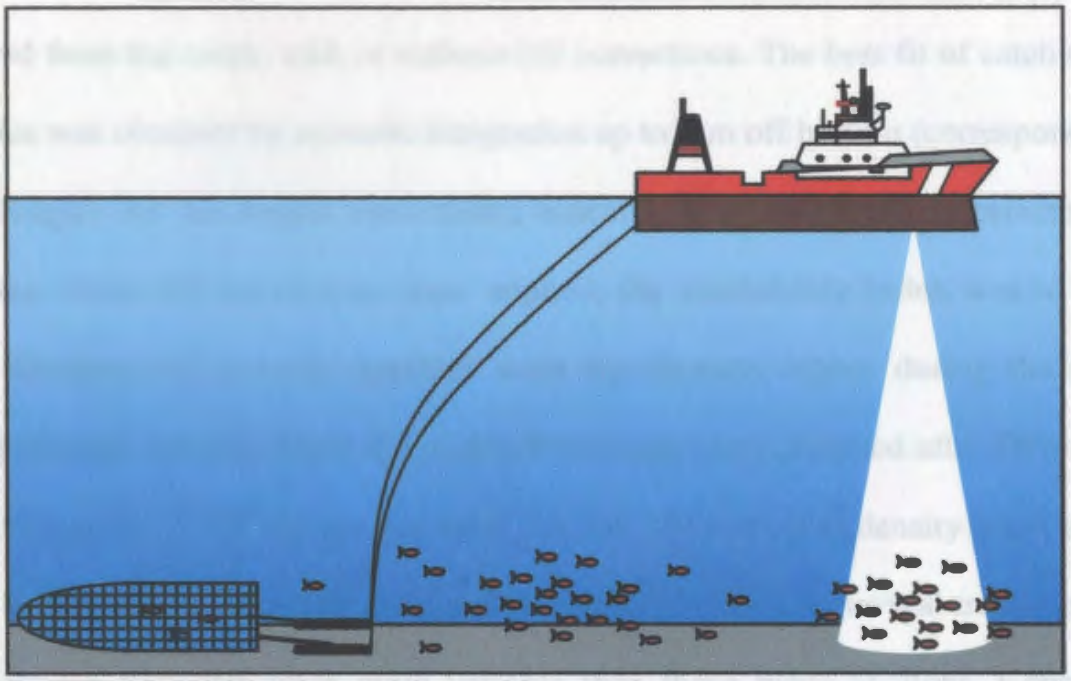


Figure 7.9. Nearest neighbor distance (in BL) estimated for maximum density observed within pelagic schools.

Chapter 8. Effects of vertical and horizontal distribution heterogeneity on acoustic and trawl surveys of redfish



8.1 Abstract

A series of acoustic-trawl experiments was conducted on Atlantic redfish (*Sebastes* spp.) on the edge of the Green and Grand Bank of Newfoundland, Canada. Redfish were on or near bottom during day and migrated vertically in the water column at night. A correction factor for the near-bottom acoustic dead zone (DZ) was developed. Total densities estimated using acoustic methods were consistently higher than densities obtained from the catch, with or without DZ corrections. The best fit of catch to acoustic densities was obtained by acoustic integration up to 5 m off bottom (corresponding to the trawl height). At this height, catchability index was near unity for uncorrected acoustic densities. After DZ corrections were applied, the catchability index was < 1 in most cases. Uncorrected acoustic densities were significantly higher during the night than during the day. No significant day-night differences were observed after DZ corrections. Within transects of 500 pings (ca 1400 m), the CV's of area density were on average 131% during the day and 35% at night. Consecutive passes of several transects indicated that daytime estimates were more variable then those made at night. I conclude that bottom trawling consistently underestimates redfish abundance and that acoustic estimates made at night provide the most reliable and least variable biomass estimates.

8.2 Résumé

Plusieurs expériences combinant échantillonnage par chalut et par méthode acoustique ont été conduites sur le sébaste de l'Atlantique (*Sebastes* spp.) dans les eaux de Terre-Neuve, Canada. Le sébaste était situé près du fond pendant le jour et migrait verticallement dans la colonne d'eau au cour de la nuit. Un facteur de correction pour la zone aveugle (ZA) près du fond a été developpé. La densité totale estimée avec la méthode acoustique était plus elevée que la densité obtenue à partir de la prise, avec ou sans corrections pour la ZA. La meilleur relation entre les densités estimées avec les deux methodes a été obtenue par integration acoustique à 5 m du fond (correspondant a la hauteur du chalut). À cette hauteur, l'index de capturabilité était proche de l'unité pour les densités acoustiques brutes. Après corrections pour la ZA, l'index de capturabilité était dans la plupart des cas < 1. Les densités acoustiques brutes étaient significativement plus elevées pendant la nuit que pendant le jour. Aucunes différences significatives entre le jour et la nuit ont été observées après corrections de la ZA. À l'intérieur de transect de 500 émissions (1400 m), les CV's de densité de surface étaient en moyenne 131% pendant le jour et 35% pendant la nuit. Des passes consécutives dans plusieurs transects ont indiqué que les estimations obtenues pendant le jour étaient plus variables que celles obtenues pendant la nuit. En conclusion, le chalut sous-estime l'abondance des sébastes et la méthode acoustique de nuit produit l'estimation de biomasse la plus fiable et la moins biaisée.

8.3 Introduction

Redfish (*Sebastes* spp) are commercially important species with semi-pelagic to demersal distribution in the north Atlantic. These fish have been surveyed using both bottom trawls and acoustic methods (Atkinson, 1989; Reynisson *et al.*, 1995; Vaskov *et al.*, 1998). Redfish have been observed to migrate from the ocean floor to intermediate layers at night (Beamish, 1966). Many types of demersal and pelagic aggregations have been observed (Gauthier and Rose, unpublished data). Such behaviors affect the catchability of redfish and generally results in higher bottom trawl catch rates during the day than at night (Konstantinov and Shcherbino, 1958; Beamish, 1966; Parsons and Parsons, 1976; Pálsson et al., 1985; Atkinson, 1989; Casey and Myers, 1998). Diel vertical migration and shoaling behavior can also influence abundance estimates derived from acoustic surveys (Olsen, 1990; Simmonds et al., 1992; Petitgas and Levenez, 1996). An important source of bias in acoustics, especially for the measurement of demersal fish, is the near-bottom acoustic dead zone, wherein fish are included in the bottom echo (Mitson, 1983). Hence, diel changes in the distribution of fish in relation to the ocean floor influence detectability and the reliability of acoustic estimates (Lawson and Rose, 1999).

In this paper, I report on experiments conducted at sea to test the effects of shoaling behavior and vertical migration on the abundance assessment of redfish. I compare density estimates obtained simultaneously with trawl and acoustic methods and assess the impact of scale of patchiness on survey methods. I also examine problems

related to acoustic detectability. My overall objective is to recommend survey strategies that minimize biases attributable to the effects of shoaling behavior and diel vertical migration.

8.4 Material and Methods

The study site was located on the edge of the Green and Grand Banks of Newfoundland in NAFO subdivisions 3Ps and 3N (Fig. 8.1). Experiments were conducted with the Canadian Coast Guard Ship Teleost on July 24 – 27, 1996, January 10 – 14, 1997 and March 30 - April 2, 1998. On each occasion large aggregations of redfish (*Sebastes* spp.) were encountered at sites with few other demersal or pelagic fish species. Further experiments were conducted on two redfish aggregations encountered on June 24 1998.

All acoustic measurements were made with an EK500 (Kongsberg, Simrad) echosounder and a ES38B 38 kHz hull-mounted split beam transducer with beam dimensions of 7.1° between half power points. Calibration was performed using tungsten-carbide and copper spheres following recommended procedures (Foote et al., 1987). During each experimental period, several transects of 1 to 9 km length were surveyed using a pulse duration of 0.8 ms and rate of 1-2 ping s^{-1}. Each transect was run more than once and at least one site was monitored over a 24 hr period. Measured volume scattering strengths (m^{-1}) were transformed to fish density (D_v, in fish · m^{-3}) using the mean backscattering cross-section ($\hat{\sigma}_{bs}$):

(1) $$D_{v} = 4\pi\left(\frac{\dot{s}_{v}}{\hat{\sigma}_{bs}}\right)$$

the 4π was added since the SIMRAD EK500 calculates spherical scattering rather than backscattering coefficients, hence the notation $\dot{s}_{v}$ to differentiate with the more common s_{v} (volume backscattering coefficient). The mean backscattering cross-section was obtained by converting the mean target strength (TS) into arithmetic form:

(2) $$\hat{\sigma}_{bs} = 10^{TS/10}$$

where TS was estimated using the TS-Length equation for redfish developed by Gauthier and Rose (2001) and the length composition of fish at each site:

(3) $$TS = 20 \text{ Log } [\text{ length (cm)}] - 68.7$$

Bottom and midwater trawls were used to identify species and measure size composition at a time and location as close as possible to the acoustic observations. Size distribution of redfish was determined by measuring the length of 200 – 500 individuals. When the distribution was normal, mean length was used to calculate mean TS. If more than one size mode was present (or if the distribution was severely skewed), TS was

partitioned in categories of 1 cm length. The area backscattering coefficient ($m^2 \cdot m^{-2}$) was obtained by integrating $\dot{s}_v$ over depth range r_1 to r_2:

$$s_a = 4\pi \cdot \text{mean}\left[\int_{r_1}^{r_2} \dot{s}_v \, dr\right] \tag{4}$$

Consequently, area fish density (fish $\cdot$ m^{-2}) was obtained by dividing the average s_a by the mean backscattering cross-section ($\hat{\sigma}_{bs}$).

At each site, the maximum distance above the ocean floor at which redfish were observed was measured and echointegration was performed in a series of 1 m bottom-locked layers. For sites that spanned a wide range of depth (for example along the continental slope), transects were divided in sections of 20 m depth increments. Midwater IYGPT and Diamond-9 Otter trawls were used at 10, 25, 50, 75, and 100 m off bottom to identify pelagic traces. The proportion of fish present in the layers near bottom was calculated by dividing the acoustic density in those layers by the total density in the water column.

A correction for the acoustic dead zone was applied using information from the distribution of S_v in the first layers above the detected bottom and the height of the dead zone (DZ). The total height loss to DZ was estimated as the sum of the bottom vertical offset (which varied between 0 and 1 m in this study), the partial integration zone ($c\tau/4$)

estimated using sound speed (c) in ms^{-1} and pulse duration (τ) in s, and the effective height (in m) corresponding to the volume loss due to the convolution of the beam. Ona and Mitson (1996) showed that this height could be estimated as:

$$h = 2404\left[\frac{d \cdot \tan^{2}\theta_{3}}{\theta_{3}^{2}}\right] \quad (5)$$

where θ_3 is the half-beam angle to the -3 dB point and d is the depth in m. This estimation assumes a flat and horizontal bottom (since a fraction of the beam curvature and width must be on a perfectly flat and horizontal surface). To account for the proportion of fish located in the acoustic "deadzone", I developed a correction factor that takes into account the distribution of the volumetric density in the first five meters above the detected seafloor:

$$DZ\ \dot{S}_{v} = \dot{S}_{v1}\left[\sum_{i=1}^{4}\left(\frac{\dot{S}_{v\,i-1}}{\dot{S}_{v1}}\right)\cdot 4^{-1}\right] \quad (6)$$

where DZ $\dot{S}_v$ is measured in dB and i represents depth layers of 1 m above the sea floor. V_1 represents the 1 m layer just above the detected bottom. The logarithmic form was used in equation (10) to allow simple linear extrapolation.

8.4.1 Trawl-acoustic comparisons

Fishing sets were conducted at 3 knots using a Campellen 1800 bottom trawl with 1400 Kg poly oval doors 44 mm codend. A Scanmar system recorded the dimensions of the net while fishing (distance from sea-floor, door and wing spread, distance of bottom to head rope). In March-April 1998, this information was used to estimate the mean wing spread during each experiment. For sets in 1996, 1997 and June 1998 mean wing spread between depths of 150 and 450 m was estimated by means of a linear regression obtained from the data collected in 1998 ($R^2 = 0.73$, DF 1,22, $F = 63.4$, $p < 0.001$):

$$WS = 0.004 \cdot d + 15.4 \quad (7)$$

where WS is the wing spread and d is the depth of the gear in m. The number of fish at each fishing site was estimated by dividing the total catch weight by the mean individual weight derived from a subsample of 200 – 500 fish. Area fish density along the trawl path was estimated as:

$$D_A = \frac{N}{WS \cdot v \cdot T} \quad (8)$$

where N is the number of fish caught, WS is the mean wing spread of the net in m, v is the vessel speed in ms^{-1} and T is the duration of the tow in s.

Acoustic records were used to match the location of the fishing area. The distance of the net behind the vessel (X) was estimated as:

(9) $$X = \sqrt{\left(L_{\omega}^{2} - d^{2}\right)}$$

where L was the amount of wire out and d was the trawl depth in m. Once the location of the trawl was determined, the acoustic backscatter within the fishing interval was integrated in sequential 1 m vertical intervals off the detected bottom. Densities obtained at different heights above bottom were compared to the density in the trawl. Linear reduced major axis regression analyses were performed to find the height at which acoustic integration best predicted densities based on the catch.

To obtain a relative index of catchability, the fish density based on the catch was divided by the density based on the acoustic method. A value equal or close to unity indicated that the trawl caught the same amount of fish as predicted using acoustic integration. Values higher than 1 indicated that the trawl caught more fish than predicted using the acoustic data while, inversely, values below 1 indicated that the trawl catch was lower than predicted.

8.4.2 Density variability

Twenty-four acoustic transects of 500 pings (approximately 1400 m) were run during both the day and night. On each transect, density was measured for every ping and the within transect coefficient of variation (CV) was expressed as a percentage:

$$CV = \frac{100 \cdot \text{standard deviation}}{\text{mean}} \tag{10}$$

Paired t-test analyses were employed to determine if overall transect mean acoustic density differed between day and night (before and after DZ corrections). Separate paired t-test analyses were also performed on trawl stations that were visited during both day and night. Several transects (also at constant length of 500 pings) were run twice over a relatively short period of time. To assess the effect of local variance on density estimates, a reduced major axis regression analyses was performed between the first and second passes of each transect. A separate analysis was performed for day and night experiments.

8.5 Results

A distinct pattern of diel migration was observed during each of the three surveys (Fig.8.2). The proportion of fish recorded in the first 10 m off the bottom increased at sunrise and remained higher during the day than at night, and decreased again at sunset (Table 8.1). The maximum distance of fish above the bottom was much higher at night.

Several discrete pelagic schools (close to the bottom) were observed during the day in July 1996 and March-April 1998. No pelagic schools were recorded in January 1997. A pattern was also observed, although not as consistently, in the area density of fish, with higher values obtained at night (Table 8.1).

The distribution of volumetric densities also varied on a diel cycle (Fig. 8.3). During the day, fish were concentrated in relatively small areas close to the bottom and volumetric densities within the aggregations were high, with average values between 0.1 and 0.4 fish per m^{-3}. Values as high as 31 fish per m^{-3} were recorded in some instances, suggesting that extinction cross section may be significant close to the bottom. At night, fish were distributed more uniformly in layers above the ocean-floor and volumetric densities averaged 0.01 fish per m^{-3} (with maximum density < 0.1 fish per m^{-3}). Fish moved to greater distances above the ocean floor as overall depth increased.

Corrections applied to the DZ appeared to follow the general shape of the S_v in the first 10 m off bottom (Fig. 8.4). The resulting DZ $\dot{S}_v$ was then converted into arithmetic form and multiplied by the estimated height of the DZ to obtain s_a. The ADZ s_a represented on average 27% of the total s_a during the day (with a maximum value of 85%). In contrast, the DZ s_a at night represented on average only 6% of the total s_a (with a maximum value of 34 % of total s_a).

The mean length of fish caught ranged from 14.8 to 32.4 cm. Fish densities within the trawl path estimated from acoustic integration were in most cases higher than densities estimated from the trawl catch (Fig. 8.5a). The best prediction of the densities estimated with the trawling method was obtained by integrating only the first five meters off the bottom, with or without the DZ corrections, for both day and night experiments (Fig. 8.5 b and c, Table 8.2). For uncorrected values, overall catchability was in most cases much lower than 1 (Fig. 8.6a). However, when only the first five meters off bottom were integrated, the catchability index was closer to unity (Fig. 8.6b). Nevertheless, the acoustic densities were almost certainly underestimates of true density, since many redfish were distributed close to the bottom and undetectable (especially during the day). When the correction for dead zone was applied to the integration of the first five meters off bottom, catchability decreased below unity (Fig. 8.6c). In every case, catchability was high only at very low acoustic densities. For corrected acoustic densities in the first 5 meters off bottom, catchability was > 1 at acoustic densities < 0.2 fish $\cdot$ m^{-2}.

Paired T-test statistics indicated that densities estimated using the trawling method were higher at day than at night at the same location (mean difference 0.27 fish m^{-2}, DF = 7, T = -2.6, $P < 0.05$). In contrast, densities obtained using acoustic methods were lower during the day than at night (mean difference of 0.6 fish m^{-2}, DF = 22, T = -2.9, $P < 0.01$). No significant differences were observed between day and night acoustic estimates when the correction was applied for the acoustic dead zone. Nevertheless, variability in fish density along a transect line was much higher during the day than at

night (Fig. 8.7). During the day, the CV was on average 131% and ranged from 89% to 215%. During the night the CV was on average 35% and ranged from 15% to 47%. Accordingly, regression analysis between consecutive passes over the same transect indicated that divergences were more pronounced during the day than at night (Fig. 8.8). During the day, the coefficient of correlation between the first and second pass was 0.57 with a slope of 0.76 ($DF = 1, 46$; $F = 63.18$, $P < 0.001$). At night, the coefficient of correlation was of 0.85 with a slope of 0.92 ($DF = 1, 41$; $F = 233.48$, $P < 0.001$). Intercepts did not differ significantly from zero in either case.

8.6 Discussion

The diel cycles in redfish distribution and shoaling observed over the three years of study were similar, except for the absence of pelagic schools in January 1997. Movement of fish towards the pelagic zone coincided with sunset, with fish returning close to the bottom at sunrise, suggesting that light is the main controlling factor for redfish vertical migration. Acoustic observation of the dispersion of fish at night has been widely documented (Weston and Andrew, 1990; Fréon et al., 1996; Brodeur and Wilson, 1998). Similar species of Sebastes in the Pacific Ocean have been reported to exhibit distinct patterns of diurnal and nocturnal shoaling behavior (Leaman et al., 1990; Stanley et al., 1998), although some species, such as the shortbelly rockfish, exhibit more pelagic distributions (Gunderson and Sample, 1977).

My data indicate that acoustic densities were consistently higher at night. The patchy and high concentration of fish close to the bottom (and into the DZ) during the day is likely to be the main reason for day-night differences. Indeed, the distribution of S_v (or fish density) in the few meters above the ocean floor suggests that a higher proportion of fish are located in the acoustic dead zone during the day than at night. Visual observation of numerous small redfish groups of 10-30 redfish in Placentia Bay using a submersible (Lawson and Rose, 1999) and observation of substantial aggregations of redfish in the Laurentian channel using remote controlled underwater cameras (D. Gordon, Fisheries and Oceans Canada, personal communication) have revealed the close association of redfish with the ocean bottom. The correction factor applied for the dead zone fit the trend in density distribution of fish close to the bottom during day and night. It is noteworthy that the significant differences observed between day and night acoustic densities were not evident if the DZ correction factor was applied. The correction factor was much larger during the day than at night, and a large correction must increase the uncertainty of any acoustic measurement. For example, when densities were low and fish were distributed only in the first few meters off bottom, the DZ correction could represent the major component of the density estimate. With no visual information on the true distribution of fish, I do not recommend using density estimates that include a large (> 25%) correction component.

In all but 5 experiments, uncorrected densities derived from acoustic integration were higher than estimated from the catch. If constant gear efficiency is assumed within

the trawl swept area (no fish herding or escapement) these acoustic data (and knowledge of redfish distribution) suggest that densities obtained using the trawling method should be higher than the uncorrected total acoustic estimates during the day and vice versa at night (because availability to trawling should be greater during day and to acoustics at night). Interestingly, trawl density most closely corresponded with acoustic data in the bottom 5 m, irrespective of day or night or acoustic dead zone correction. This zone corresponds closely to the head rope height of the Campelen trawl (4.5 m). Without the DZ correction factor, the catchability within this stratum was close to unity. However, the acoustic values were undoubtedly underestimated and required some adjustment for the DZ. After corrections, the catchability index was less than one at all but very low acoustic density. These results suggest that the catching efficiency of the trawl was less than perfect during both day and night. However, higher catch rates occurred during the day because a larger proportion of the fish were closer to the bottom. On his analysis of 6898 fishing sets on redfish in the Northwest Atlantic, Atkinson (1989) found differences in catch rates of approximately 4-fold by number and 5-fold by weight among diel periods. Overall day and night differences were not as great, but significant. Several other studies have reported differences of 2 to 4-fold differences between day and night (Beamish, 1966; Parsons and Parsons, 1976; Pálsson et al., 1985; Casey and Myers, 1998). Trawls may be more effective during the day because of visual herding (Wardle, 1993) and reduced reaction of the fish to the trawl at night (Michalsen et al., 1996). However, Engaas and Ona (1990) showed that the herding process was equally efficient during day and night, but observed differences in the way fish entered and avoided the

trawl opening. Yousif and Aglen (1999) reported that cod up to 100 m above bottom might be scared down into the trawl. In another study on cod, saithe, redfish and other demersal species, Aglen (1996) obtained significant correlations between acoustic and trawl density at heights of 30-40 m above the bottom (and higher for haddock). Aglen (1996) concluded that fish below a certain depth were scared downward into the trawl, although the redfish results are limited (8 experiments). Ona and Godo (1990) observed that the main source of disturbance for the onset of such diving behavior was produced by propeller cavitation and that such avoidance reaction for saithe was not significant below 200 m depth. My data did not suggest any diving behavior in redfish at depths > 200 m where the experiments were conducted and predictions of catch based on acoustic densities within the trawl path were consistently higher than the observed trawl catch.

Detailed analysis of acoustic densities indicated that redfish distribution was more heterogenous during the day than at night. Daytime patches were found on a relatively small spatial scale (tens to hundreds of m). Small-scale patchiness suggests that even small differences in the position of acoustic relative to trawl path could result in large differences in density values. In keeping with this suggestion, mean acoustic densities measured in consecutive passes over the same transect showed much higher variability during the day than at night. At night, redfish were broadly distributed into the water column and densities were more homogenous than during daytime. Density values uncorrected for DZ bias were consistently higher at night than during day, because fewer fish were near bottom.

Scattering layers of pelagic organisms (mainly euphausiacea), which were very dense at night, could introduce a bias in my acoustic comparisons. On the acoustic assessment of redfish in the Irmenger sea, Reynisson et al. (1995) indicated that scattering layer mixing with redfish at night makes separation of these 2 types of scatterers difficult. At a frequency of 38 kHz, low densities of euphausiids are often not detected with typical noise threshold (eg –70 to –75 dB at 20logR). However, when euphausiids are in very dense aggregations, scattering from these organisms cannot be eliminated without loss of fish echoes. Reynisson (1996) demonstrated the importance of threshold induce bias in the echo-integration of single fish. In this study, a threshold of -75 dB for volume backscattering strength was chosen as a compromise between bias and the exclusion of exogenous targets (scattering layer). When discrimination of redfish was impossible, data were not used. Another potential source of bias between day and night was the extinction of sound in dense schools during the day, thus producing a shadowing effect (Foote et al., 1992). Appenzeller and Leggett (1992) suggested that this bias could be important in freshwater fish. However, results from Furusawa et al. (1992) revealed that extinction was negligible even for the thickest Pollock school measured. The range of densities observed in this study suggests that bias due to exctinction is likely negligible, with the exception of the highest densities encountered during the day. These conditions were, however, infrequent and consisted of small shoals located directly on the bottom.

In conclusion, high local variability in the distribution patterns of redfish was observed. At the scale of trawl and acoustic measurements, redfish appear to exhibit strong heterogeneity in density, but more uniform and continuous distributions at night. I conclude that the most reliable estimates of redfish density can be achieved employing acoustic methods at night, while the fish are vertically migrating and dispersed in the water column. Any variations in TS caused by tilt angle during migration are likely to be less for *Sebastes* than for other migrating species such as the gadoids (Gauthier and Rose, in press), and are less likely to be the source of severe bias on acoustic surveys.

8.7 Acknowledgements

I thank the crew of the CCGS Teleost, C. Lang, R. Forward, W. Hiscock and G.L. Lawson for assistance at sea. Funding came from the Canada Department of Fisheries and Oceans (Redfish Multidisciplinary Research Program) and the Natural Sciences and Engineering Research Council of Canada Industrial Chair in Fisheries Conservation at Memorial University of Newfoundland

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8.9 Tables

Table 8.1. Statistics for the day - night differences observed in the density of fish (fish · m^{-2}), the proportion of fish in the 10 m bottom layer (BL_{10} in m) and the maximum distance of fish from the bottom (in m) for separate transects surveyed for 24 hours during each mission. Significant P values are indicated in bold.

Mission	Variable	Mean		Levene test for equality of variance		T-test for equality of mean			
		Day	*Night*	*F value*	*P*	*DF*	*Mean difference*	*T value*	*P*
July 1996	Density	0.82	2.01	1.14	0.26	11	-1.19	5.56	**<0.001**
	Proportion in BL_{10}	60.0	29.0	0.32	0.58	11	31.3	-2.6	**0.025**
	Distance off bottom	26.0	59.0	0.61	0.45	11	-32	3.6	**0.004**
January 1997	Density	0.14	0.66	7.58	0.02	15	-0.53	3.1	**0.007**
	Proportion in BL_{10}	75.6	38.0	5.29	0.04	15	37.5	-4.3	**0.001**
	Distance off bottom	13.1	59.6	3.65	0.08	15	-46.4	5.5	**<0.001**
April 1998	Density	0.71	1.23	0.27	0.61	14	-0.5	3	**0.009**
	Proportion in BL_{10}	43.5	31.5	4.3	0.06	14	17.9	1.7	0.105
	Distance off bottom	27.6	57.4	0.57	0.46	14	-29.8	-3.38	**0.005**

Table 8.2. Statistics for the regression model of observed catch density on density estimated by acoustic methods. Correction is for bottom dead zone (see results for details of dead zone estimation).

Model	R^2	Slope	DF	F	P
Uncorrected total density	0.21	0.14	1, 35	10.75	0.002
Uncorrected density at 5 m	0.66	0.83	1, 35	70.73	<0.001
Corrected density at 5 m	0.64	0.44	1, 35	65.17	<0.001

Figure 8.1. Map of Newfoundland and the Continental Shelf. The circles represent area surveyed during our acoustic-trawl experiments.

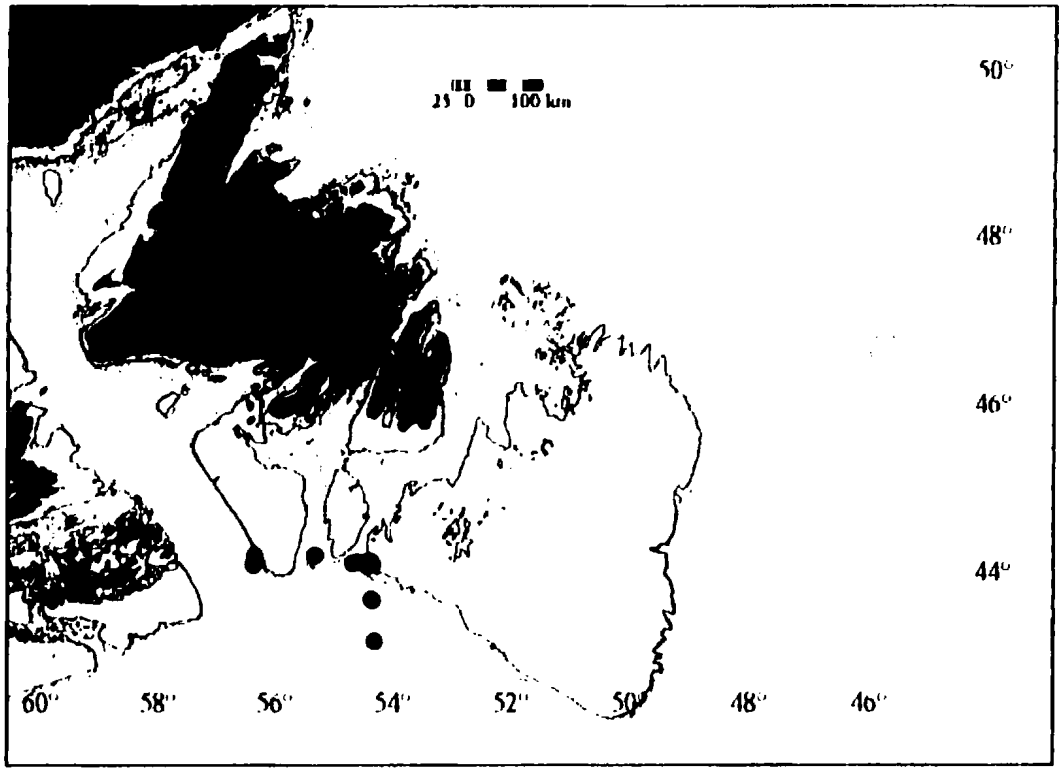

25 0 100 km
50°
48°
46°
44°
60°
58°
56°
54°
52°
50°
48°
46°

Figure 8.2. Average area density (fish m^{-2}), proportion of fish in the first 10 m off the detected bottom (BL_{10}), maximum distance of fish from the bottom (in m) and numbers of pelagic schools for transects acoustically surveyed over 24 hours in July 1996, January 1997 and April 1998. The doted lines indicate time of sunrise and sunset.

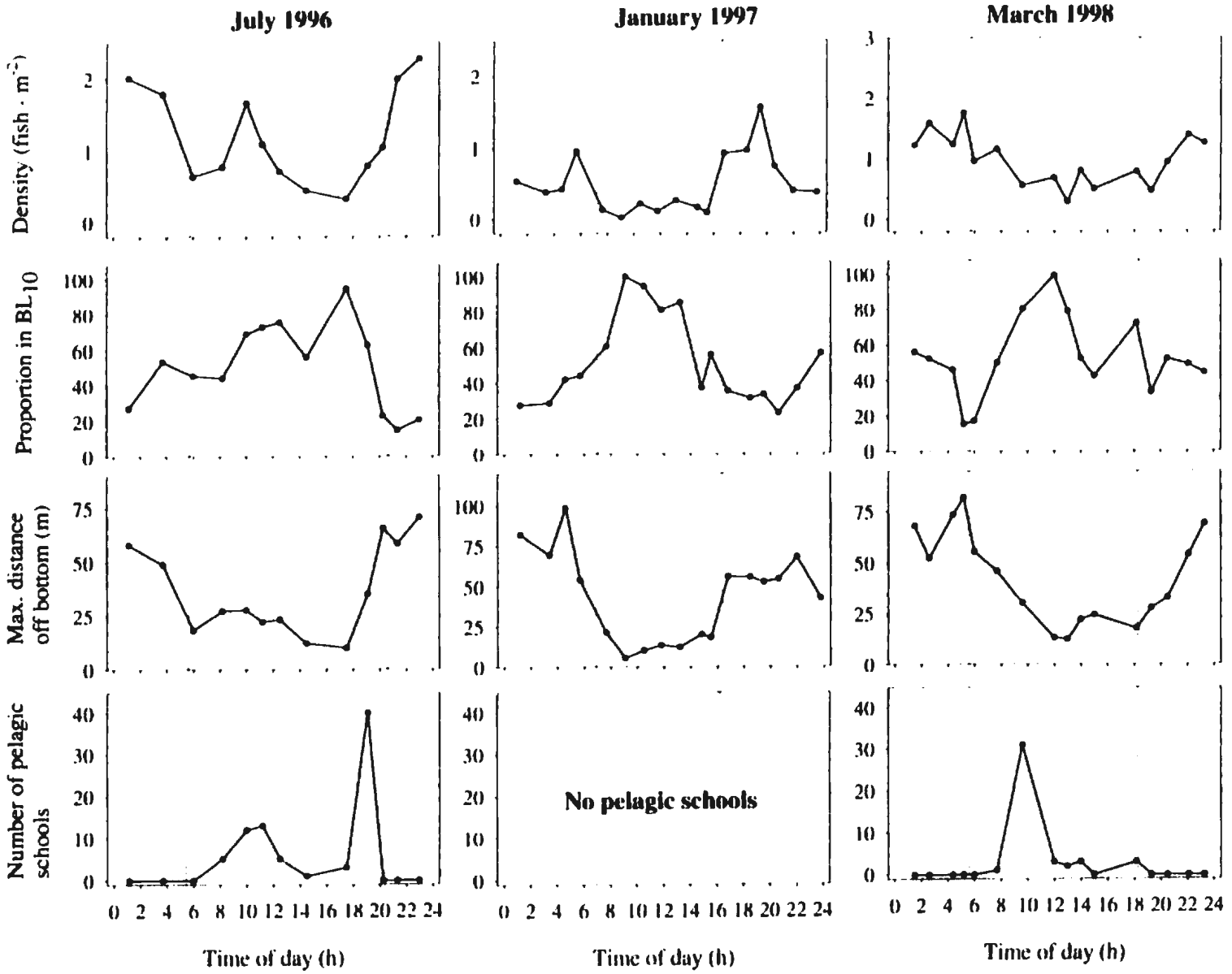

July 1996
January 1997
March 1998
Density (fish · m⁻²)
Proportion in BL10
Max. distance off bottom (m)
Number of pelagic schools
No pelagic schools
Time of day (h)
Time of day (h)
Time of day (h)

Figure 8.3. Distribution of volumetric density (fish · m^{-3}) above the detected bottom by total water depth along a representative transect surveyed during day and night.

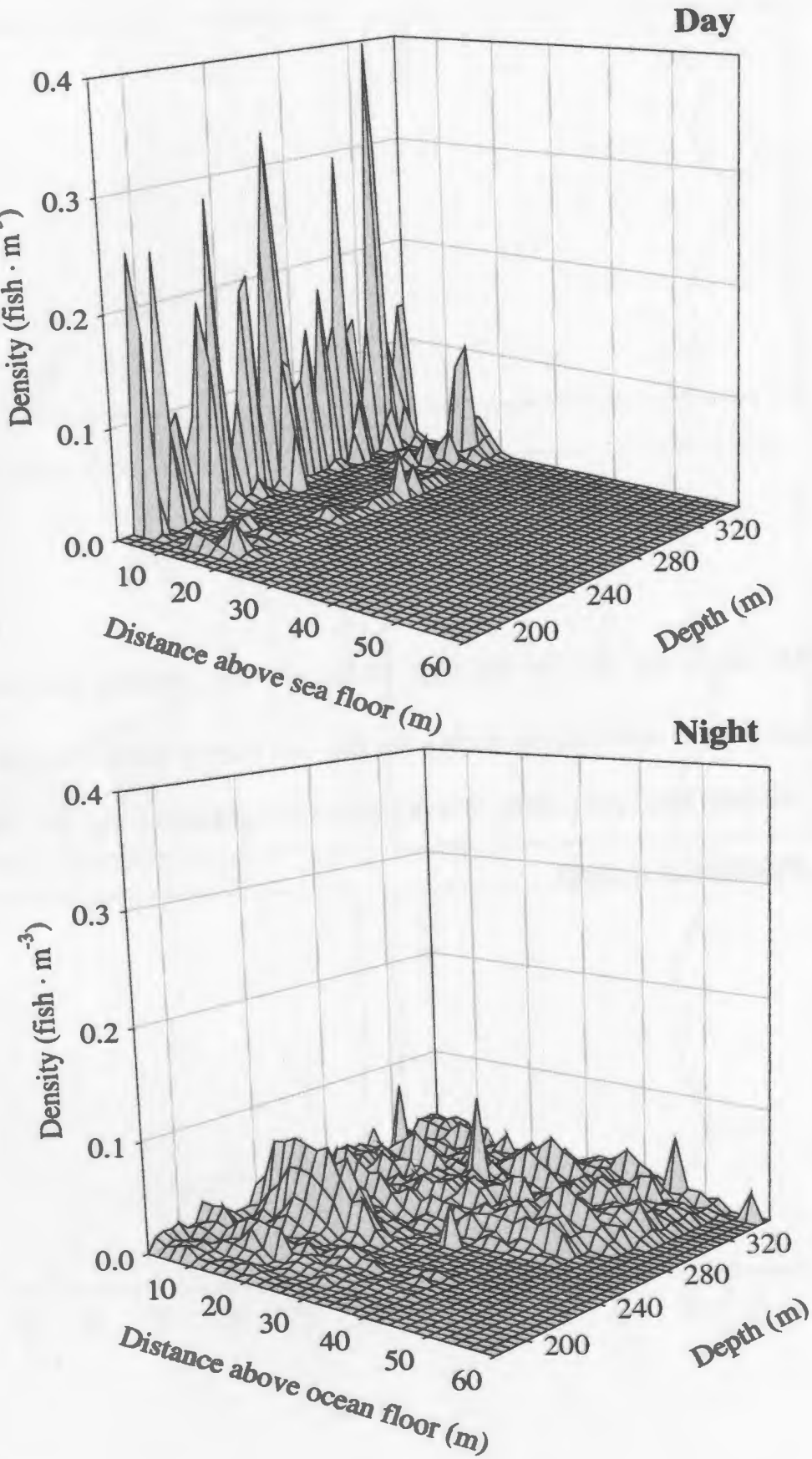

Day
0.4
0.3
0.2
0.1
0.0
Density (fish · m-3)
10
20
30
40
50
60
Distance above sea floor (m)
200
240
280
320
Depth (m)
Night
0.4
0.3
0.2
0.1
0.0
Density (fish · m-3)
10
20
30
40
50
60
Distance above ocean floor (m)
200
240
280
320
Depth (m)

Figure 8.4. Profile of $\dot{S}_v$ (in dB) in the first 10 m off the detected bottom for 3 representative aggregations encountered during the day and during the night. The dotted lines delimit the acoustic dead zone (DZ). Curves were extrapolated to the DZ using the correction factor described in the text.

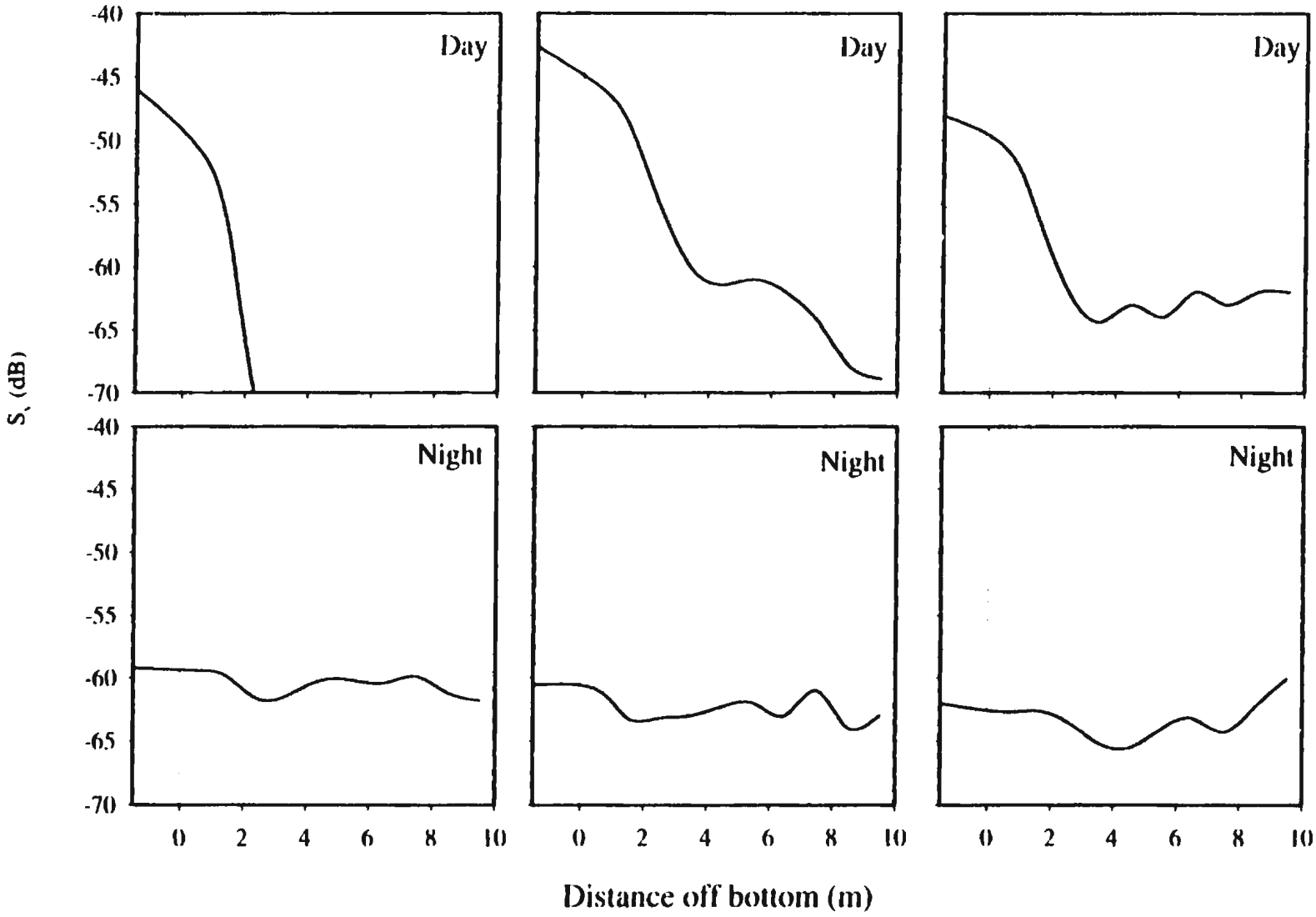

Day
Day
Day
Night
Night
Night
-40
-45
-50
-55
-60
-65
-70
0
2
4
6
8
10
S, (dB)
Distance off bottom (m)

Figure 8.5. Comparisons of area density (fish · m^{-2}) estimated from the catch and the acoustic method. a) uncorrected total acoustic density, b) uncorrected acoustic density to 5 m off bottom, c) acoustic density to 5 m off bottom, corrected for dead zone underestimation as described in text. Circles represent day experiments, squares represent night experiments.

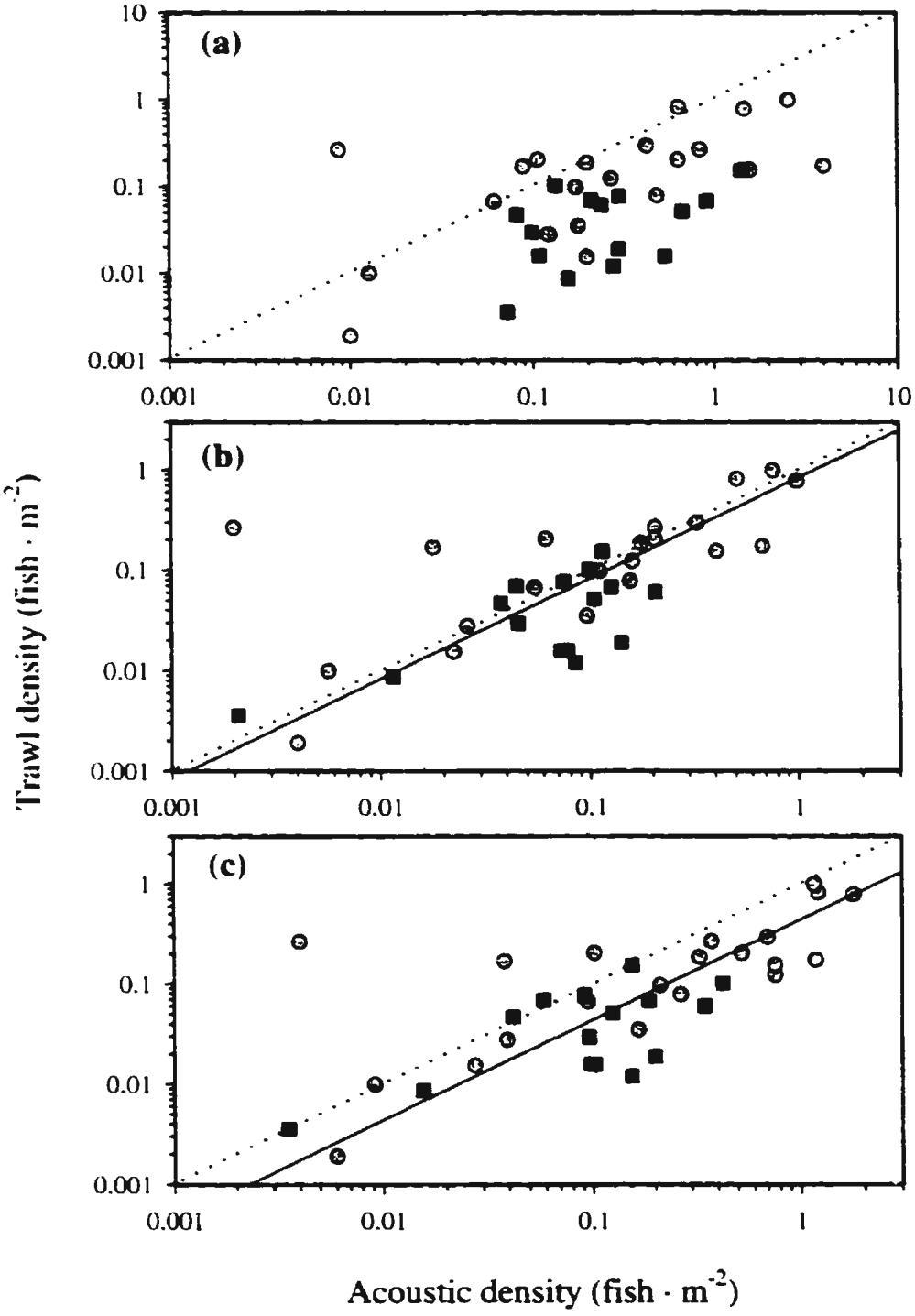
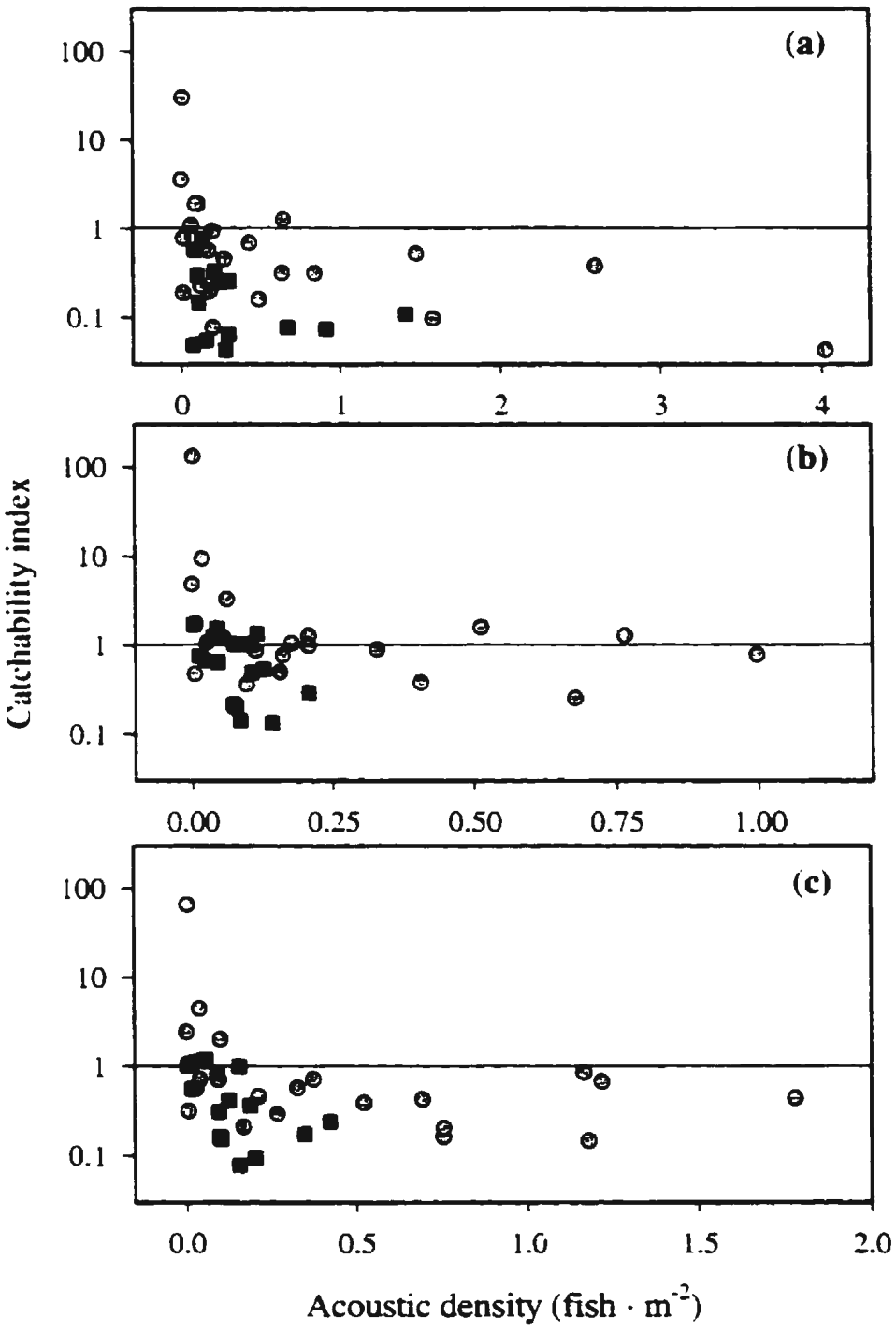

(a)
(b)
(c)
10
1
0.1
0.01
0.001
0.001
0.01
0.1
1
10
Trawl density (fish · m-2)
Acoustic density (fish · m-2)

Figure 8.6. Relative catchability index as a function of acoustic density (fish · m^{-2}). a) uncorrected total acoustic density, b) uncorrected acoustic density to 5 m off bottom, c) acoustic density to 5 m off bottom corrected for dead zone underestimation as described in text. Circles represent day experiments, squares represent night experiments


(a)
(b)
(c)
100
10
1
0.1
0
1
2
3
4
0.00
0.25
0.50
0.75
1.00
0.0
0.5
1.0
1.5
2.0
Catchability index
Acoustic density (fish · m-2)

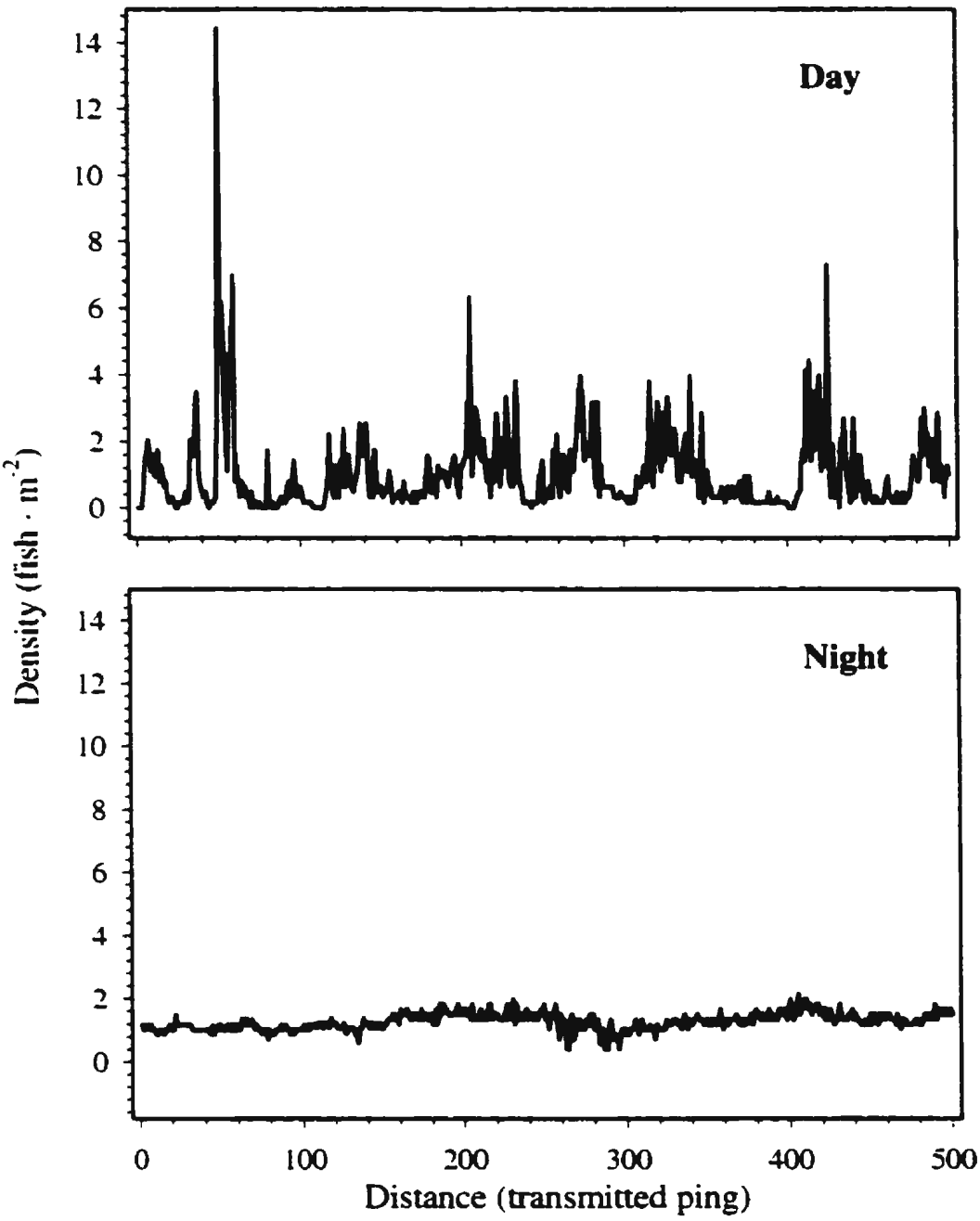


Figure 8.7. Distribution of density (fish · m^{-2}) along a representative 500 ping (ca 1400 m) long transect visited during the day and during the night. During the day mean density was of 1.06 fish · m^{-2} with a standard deviation of 1.25. During the night mean density was of 1.28 fish · m^{-2} with a standard deviation of 0.27.

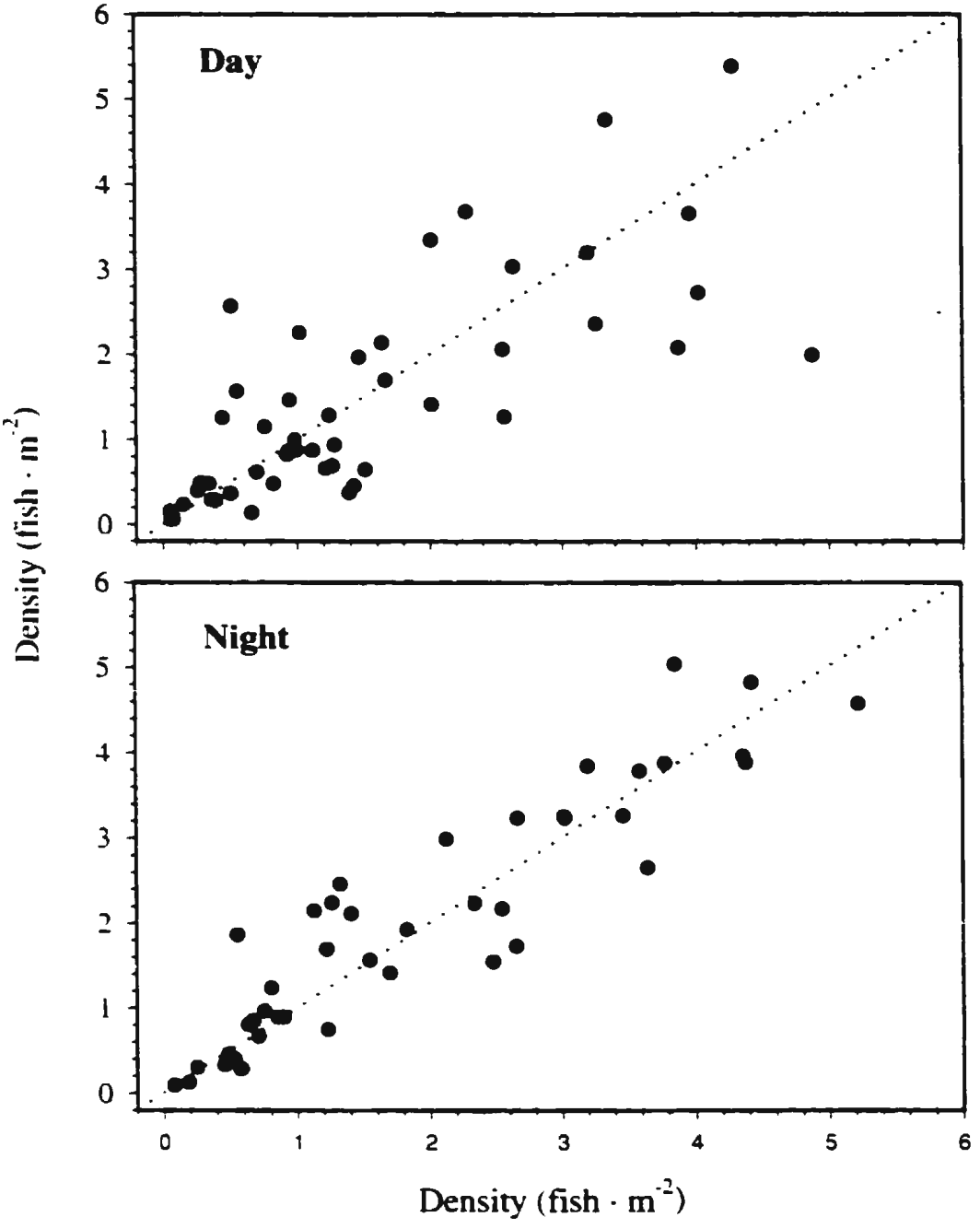


Figure 8.8. Correlation between the density (fish · m^{-2}) acoustically estimated on the first and second pass of several transects visited during the day and during the night.

Chapter 9. Summary

This thesis reports on the first extensive research on the acoustic properties and characteristics of Atlantic redfish. Acoustic target strength (TS) was measured on encaged live individuals. Experimental manipulation of deep-sea fish with swimbladders can be problematic. A technique to capture and maintain individuals alive was developed and TS measured on fish that were in excellent condition. Several *in situ* TS experiments were also conducted at sea. Constraints of *in situ* TS measurements were identified and techniques to minimize biases have been proposed. The density of organisms and the measurement scales at which the number of fish per sample volume was estimated were of critical importance. A new index (based on echo counts) was developed to help diagnose potential biases caused by multiple target scattering, and TS biases related to range and threshold effects were examined using a deep-tow and hull mounted system. The target strengths obtained from *in situ* measurements were consistent with the experiments on encaged fish. *Ex situ* and *in situ* pooled data indicated a TS-Length model of:

$$TS\ (dB) = 20\log[\text{length (cm)}] - 68.7$$

Behavior of fish also represents an important determinant of their acoustic properties. Based on *in situ* observation of TS and an experiment on an encaged fish, I proposed that redfish possess an endogenous cycle in the secretion and resorption of

swimbladder gas. Under this hypothesis, the TS of redfish would not significantly change throughout the range of their diel movements. Shoaling behavior can also have major impact on attempts to survey abundance and distribution of redfish and other species.

Throughout three years of study, many different types and scales of aggregations were observed for redfish. During the day, fish generally formed dense shoals near or close to the ocean floor. Patches were found at scales of tens to hundreds of meters. Formation of pelagic schools was highly variable. When present, schools were typically close to dense aggregations on the bottom and exhibited high variability in size, shape, and density. At night, fish dispersed in the water column and their distribution was more homogenous. This behavior coincided with the vertical migration of scattering layers composed mainly of euphausiids, an important prey of redfish. The feeding migration of redfish appeared to be partly limited by depth, and the maximum vertical range of their migration appeared to be limited by a small relative change in hydrostatic pressure. Size assortive shoaling was observed throughout the study area. Bottom trawl catch indicated an increase of mean fish length with depth and increased variance in length in shallower areas. These findings improved our knowledge of redfish shoaling behavior and acoustic characteristics.

Dynamics and structure of fish aggregations play important roles in the interpretation of survey results. Trawl estimates consistently underestimated redfish density assessed acoustically. Comparisons of trawl and acoustic surveys indicated that

the best estimate of fish density could be obtained using acoustic methods while fish are dispersed in the water column at night. During the day, high levels of local variance at the scale of trawl and acoustic measurement lead to increased uncertainty in area density estimates.

Redfish is a good candidate for fisheries acoustic research, and acoustic methods can significantly improve knowledge of their abundance, distribution, and ecology. This work not only provides detailed information on the acoustic properties and shoaling behavior of Atlantic redfish, but also identified constraints for their assessment, and provides reasonable approaches to obtain appropriate acoustic TS measurements and improve survey design.

Fin

"Fish, I love you and respect you very much. But I will kill you dead before this day ends"
Hemingway (*The Old Man and the Sea*)